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EXPEDITIOUS METHODS FOR
SITE CHARACTERIZATION AND RISK ASSESSMENT
AT DEPARTMENT OF DEFENSE
HAZARDOUS WASTE SITES
IN THE REPUBLIC OF KOREA

THESIS

Dean H. Hartman, Captain

AFIT/ENV/99M-7

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THESIS

Presented to the Faculty of the Graduate School of Engineering

Of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental Management

Dean H. Hartman, Captain

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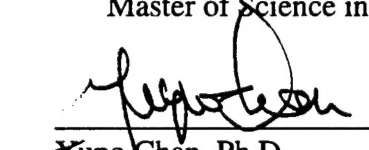Presented to the Faculty of the Graduate School of Engineering

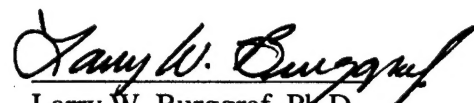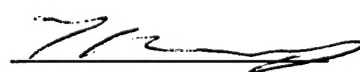Of the Air Force Institute of Technology

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<div align="right">Dean H. Hartman</div>

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Abstract

The overall goal of this research was to provide Department of Defense (DoD) decision-makers in the Republic of Korea (ROK) with innovative site characterization technologies and risk assessment methods to meet their needs in obtaining hazardous waste site data and then prioritizing those sites for remediation based upon risk. In support of this goal, the study examined the following: 1) primary sources and types of existing contamination at DoD installations in the ROK, 2) available site characterization data, 3) criteria to be used in selecting innovative site characterization technologies, 4) costs and capabilities of the innovative site characterization technologies, 5) risk assessment or risk-based corrective action (RBCA) methods available for employment at our Korean installations, 6) criteria to be used in selecting the preferred risk assessment or RBCA method, 7) data requirements for applying the risk assessment or RBCA methods, and 8) advantages and disadvantages of the risk assessment and RBCA methods.

The research approach first entailed a review and evaluation of relevant site characterization methods, principles, and technologies, as well as risk assessment and RBCA principles and methods. A Multiple Criteria Decision Making methodology was utilized along with the decision-maker's preference structure to rank the technologies and methods based upon the unique requirements and constraints of DoD installations in the ROK. Criteria and preference structure development used in the selection of the preferred characterization technologies and risk assessment/RBCA methods was primarily accomplished through a comprehensive decision-maker survey, and secondarily through interviews during a site visit to Korea and additional literature review.

Results revealed that the decision-maker preferred innovative site characterization technologies producing data of high quality and a flexible RBCA method that permits the establishment of sound remedial goals. Future research is required to evaluate the feasibility of remedial alternatives once data are collected and remedial policy is established.

I. INTRODUCTION

A. Overview

Increased environmental awareness and the resulting regulatory response in the United States (U.S.) over the past three decades has led to the identification and remediation of countless hazardous waste sites. As a primary contributor to hazardous waste generation, the Department of Defense (DoD) had and continues to have an important role in the remediation effort. Just as Americans value their right to a quality environment, citizens of the Republic of Korea (ROK) and DoD military personnel serving in the ROK also value and have a right to clean air, land, and water. The DoD has had a presence in the ROK since before the Korean War. Like their stateside counterparts, DoD installations in the ROK have generated hazardous wastes in support of peacetime and wartime missions. Disposal practices of the past, accidental spills, and containment system failures all create the likelihood of hazardous waste contamination at U.S. DoD installations within the ROK (Oshiba, 1997:193).

In her speech at the Third Annual Pacific Rim Environmental Conference, Ms Wasserman-Goodman, the Deputy Undersecretary of Defense for Environmental Security, told military environmental managers from throughout Asia and the Pacific that the environmental security program was created by the administration to achieve several fundamental goals. A primary goal was:

> ...to fully integrate environmental considerations into the way we do business in defense. This means responsibly managing environmental resources in all of our installations and activities, and complying with all applicable laws, treaties, directives and executive orders. (Wasserman-Goodman, 1994)

In fact, two of the six major objectives of DoD's environmental security program are to clean-up and reduce risk from contaminated sites, and to be responsible stewards of the land DoD holds in public trust (Wasserman-Goodman, 1994).

In a 1998 Earth Day letter, Vice President of the U.S. Albert Gore, Jr. reiterated our national commitment to global environmental quality. He wrote:

> We have moved beyond cold war definitions of the United States' strategic interests. Our foreign policy must now address a broad range of threats—including damage to the world's environment—that transcend countries and continents and require international cooperation to solve. Our children's future is inextricably linked to our ability to manage the earth's air, water, and wildlife today. (Gore, 1998)

In conjunction with Vice President Gore's letter, U.S. Secretary of State Madeleine Albright also presented a letter reaffirming U.S. foreign policy priorities. She wrote:

> Not so long ago, many believed that the pursuit of clean air, clean water, and healthy forests was a worthy goal, but not part of our national security. Today environmental issues are part of the mainstream of American foreign policy....The environmental problems we currently face are caused by human beings and these problems can be solved if America works in partnership with governments that share our commitment to a cleaner and healthier world. (Albright, 1998)

The ROK appears to be a government willing to share this commitment. In 1980, South Korea formed the Environmental Agency to oversee environmental matters within the country. In 1990, the Agency was replaced by the Ministry of Environment (MOE) (America Re-Insurance, 1998:25). The MOE is now charged with the responsibility of enforcing environmental regulations within the ROK. Korea has several environmental laws directed toward maintaining environmental quality. Starting with the Environmental Management Corporation Act in 1983, and continuing with the Basic Environmental Policy Act (1990), the Toxic Chemical Control Act (1990), the Air Quality Control Act (1990), the Water Quality Control Act (1990), the Solid Waste

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Management Act (1991), the Drinking Water Management Act (1995), the Soil Preservation Act (1995), and a host of others, Korea has focused considerable effort on establishing a legislative and regulatory framework to promote environmental quality (Oshiba, 1997:Appendix 3-2,3).

B. Background

Passage of sweeping environmental legislation, such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) set the stage for hazardous waste site identification, characterization and remediation within the U.S. Enacted by the U.S. Congress in 1980, CERCLA's impetus was the emerging realization that inactive hazardous waste sites presented great risk to public health and the environment and that existing law did not address these abandoned disposal sites (Sullivan, 1997:430). For DoD installations overseas, the nebulous phrase "imminent and substantial endangerment" outlined in DoD Instruction (DODI) 4715.8, *Environmental Remediation for DoD Activities Overseas*, has been used as the primary driver of hazardous waste site remediation activities. This requirement, however, is subject to broad interpretation and has provided a great deal of latitude on whether or not to conduct site characterizations, assess risks, or implement remedial actions (Oshiba, 1997:178-179).

DoD Policy and U.S. Law. Oshiba provided a comprehensive review of DoD hazardous waste remediation policy. He found no laws, U.S. Codes, regulations, or international agreements compel DoD to remediate hazardous waste contaminated sites in Korea (Oshiba, 1997:48). The Defense Environmental Restoration Program (DERP) and the Defense Environmental Restoration Account (DERA), which funds hazardous waste

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site investigation and remediation, do not apply in Korea (Oshiba, 1997:49). Specific

boundaries on the application of DERA were established by law, restricting expenditure

of DERA funds to restoration actions within the U.S. These boundaries create a

resource-constrained environment, and monies to perform hazardous waste site

evaluation and restoration overseas must be taken from other accounts. However, the

DERP did require the Secretary of Defense to develop policy with respect to cleaning up

environmental contamination at military installations located outside the United States

(Oshiba, 1997:48-49). Thus, although resources are constrained and the DERP does not

specifically apply, DoD has developed directives aimed at filling this policy gap.

DoD Directive (DODD) 4715.1, *Environmental Security*, indicates that it

is DoD policy to display environmental security leadership worldwide and support the

national defense mission by "...protecting, preserving, and when required, restoring, and

enhancing the quality of the environment," as well as "...reducing risk to human health

and the environment by identifying, evaluating, and where necessary, remediating

contamination resulting from past DoD activities" (DoDD 4715.1, 1996:2). The

Directive further defines restoration as the identification, evaluation, containment,

treatment, and/or removal of contamination so that it no longer poses a threat to public

health and the environment. While risk assessment may support a decision that remedial

actions are not required, the Directive explicitly requires that characterizing potentially

hazardous sites and assessing risks to personnel at those sites be carried out.

DOD Instruction (DODI) 4715.8, *Environmental Remediation for DoD*

Activities Overseas, further emphasizes the need for site characterization and possible

remedial action at our overseas installations. The following are cited within this Instruction as three of the responsibilities of the Heads of DoD Components:

1. Remedy known environmental contamination to the extent required by this instruction and the country-specific policy established by environmental executive agents;

2. Establish country-specific remediation policy to ensure consistent remediation of DoD-contaminated sites in the host nation, and;

3. Define, or provide procedures to define, the appropriate level of remediation at contaminated sites. (DODI 4715.8, 1998:2-3)

This body of DoD requirements clearly points to the need to characterize installations within the ROK so that decisions can be made on the need for future actions and potential allocation of scarce resources.

The DoD components operating in the ROK adhere to requirements outlined in the *Environmental Governing Standards* (EGS). The EGS incorporates applicable DoD Directives, Instructions, policy and procedures into an environmental compliance baseline that United States Forces in Korea (USFK) installations and operations should strive to adhere to within budgetary constraints (USFK, 1997:1-1). The EGS, however, specifically states, "these Environmental Governing Standards do not apply to...the determination or conduct of remedial or cleanup actions to correct environmental problems caused by past DoD activities" (USFK, 1997:1-1). Thus, no formal site characterization, risk assessment, nor remedial policy is outlined in the EGS.

Since the EGS does not apply to the determination or conduct of remedial cleanup actions, policy on requirements must be found elsewhere. As previously stated, DODD

4715.1 and DODI 4715.8 outline the scope of DoD responsibilities with respect to identifying and evaluating hazardous waste contamination at overseas installations. Deputy Secretary of Defense Memorandum, "Environmental Remediation Policy for DoD Activities Overseas," dated 18 October 1995, contains additional remedial policy guidance applicable to DoD installations in the ROK (DODI 4715.8, 1998). USFK had previously attempted to establish a formal remediation policy, drafting a memorandum to implement DoD remediation policy in Korea. However, this draft memorandum was never finalized and issued due to the inability of stakeholders to achieve consensus (Anderson and Kwon, 1998). Thus, while the EGS does not apply to determination of the magnitude of contamination nor the risks posed by hazardous waste sites in the ROK, applicable DoD Directives, Instructions and policy do exist and direct action.

Relevant Republic of Korea Issues. Oshiba disCVered that many factors have the potential to influence DoD hazardous waste policy in the ROK. One such factor is increased valuation of the environment by the Korean public. He found that the Korean government and general public are scrutinizing DoD operations to determine their effect on the Korean environment and that the ROK government continues to press USFK for access to DoD installations in order to assess contamination (Oshiba, 1997:173). Another factor was the passage of an extensive body of environmental legislation by the ROK. This legislation included 24 primary Acts from 1983 to 1995, and clearly points to a concerted effort to establish and refine a comprehensive environmental legal framework (Oshiba, 1997:Appendix 3-2, 1-2). Still another factor is the commitment to preserving the environment shared by many ROK "grass-roots" organizations. Oshiba disCVered that environmental Non-Governmental Organizations (NGO) in Korea numbered

approximately 270 as of 1995, and these NGOs have been active in studying the environment just outside the boundaries of DoD installations in Korea (Oshiba, 1997:4). A final factor is the fact that the ROK Ministry of National Defense (MND) has taken the initiative to determine the extent of hazardous waste contamination on their installations, and this may result in pressure for U.S. DoD installations to do the same. MND has programmed in excess of US$25 million to characterize sites disCVered during joint MND/MOE inspections in 1995 and 1996 (Oshiba, 1997:141-142). This effort clearly demonstrates the commitment of the Korean MND towards action concerning hazardous waste site characterization.

Relevant International Issues. As the U.S. continues to return overseas installations back to the various host nations, lessons are learned on the importance of environmental quality and the price of hazardous waste contamination at these installations. In Germany, for example, the U.S. military totals the value of improvements it has made to an installation scheduled for return, and then subtracts the cost of environmental damage done (Hamer, 1993:20). The resulting sum is what the DoD calls "residual value" of the installation. The enormous remediation cost estimates for returned installations therefore result in the forfeiture of substantial amounts of money by the U.S. military (Hamer, 1993:20). Oshiba noted that in Germany alone, DoD components have returned nearly 650 installations or facilities since 1990 in which residual value included substantial cleanup cost offsets (Oshiba, 1997:183). Currently in Panama, although no formal Status of Forces Agreement (SOFA) exists requiring environmental restoration, pressure is being applied by Panamanian government officials for U.S. military components to remediate sites prior to returning land to the host nation

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(Harner, 1998). In excess of $500K are programmed in fiscal year 1999 funds to characterize and remediate a handful of contaminated sites at Howard AFB (Harner, 1998). While policy and treaty requirements are being interpreted, Howard AFB environmental personnel acknowledge this programmed amount may only address a very small part of the hazardous waste contamination problem (Harner, 1998). Canada serves as another example of where the U.S. government elected to pay restitution for cleanup of hazardous waste sites overseas (Oshiba, 1997:183).

Oshiba found that policy-makers believed it would become increasingly difficult to defend Status of Forces Agreement (SOFA) provisions allowing return of U.S. installations to the ROK without restoration of environmental contamination as the U.S. continues to agree to some sort of restitution in other countries (Oshiba, 1997:183). He found that as the U.S. continues to set a precedent by compensating host nations for contaminated sites caused by DoD activities, regardless of any SOFA or other international agreement, the case supporting restoration in foreign countries becomes much stronger, potentially leading to its adoption as a tenet of international law.

Mission Impact. One of the most critical impacts of potential hazardous waste contamination at DoD installations in the ROK is the deterioration of mission capability. Oshiba found that drinking water wells at several main operating bases (MOBs) and collocated operating bases (COBs) are contaminated with petroleum, oils, and lubricants (POLs) and organic solvents, potentially impacting warfighting capabilities of DoD and ROK military units (Oshiba, 1997:195). This finding could have grave consequences concerning mission readiness during wartime activities. Protection of the health and safety of U.S. soldiers, sailors, airmen and their ability to carry-out their mission may be

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in question when the severity of and risk from hazardous waste contamination remains virtually unknown.

In addition, the public perception by the citizens of Korea on how the U.S. DoD addresses hazardous waste contamination may "have important implications concerning the continued viability of DoD installations and operations in the ROK," and may influence our continued access to Korean land, sea, and airspace (Oshiba, 1997:4-5).

Summary. Oshiba established through his interviews with DoD and USFK officials that "...suspected and confirmed hazardous waste sites, contaminated primarily with petroleum, oils, and lubricants (POL), organic solvents, and heavy metals, exist at numerous [DoD] locations throughout the peninsula" (Oshiba, 1997:192). Oshiba pointed out that at all DoD installations operating in the ROK, including those with confirmed contamination, the scope of the problem remains unknown. He proposed that additional investigation is required to adequately characterize the site hydrogeology, locate contaminant source(s), estimate the quantity of contaminant(s), predict contaminant fate and transport, and assess risk to human health (Oshiba, 1997:194).

In order to address these hazardous waste contamination problems at DoD installations in the ROK, a necessary first step is for DoD decision-makers to evaluate the severity of contamination and assess the resulting risk posed to human health. As discussed, DoD Directives, Instructions and policy require such actions. The contamination problem may pose a threat to our wartime capabilities, as well as to our access to installations in Korea. A growing level of attention to hazardous waste site contamination within the ROK MND shows their concern on this matter. In addition, U.S. experience with the Base Realignment and Closure (BRAC) process in Europe,

Central America, Canada and the U.S. has shown that knowledge of the type and degree of contamination is essential. In order for USFK to have the information it requires to be able to develop an intelligent environmental policy, data outlining site contamination and risks posed are necessary.

C. Problem Statement

In order to respond to DoD policy regarding hazardous waste sites at overseas installations, increased valuation of the environment by the Korean public, evolving Korean environmental regulations, and recent international precedents regarding environmental restoration of U.S. installations overseas, as well as to protect the health and well-being of those living and working on or near our installations, USFK must develop an intelligent strategy with regard to remediation issues in the ROK. In order to develop such a strategy and prioritize hazardous waste site remediation, if remediation is indeed required, DoD policy makers in the ROK must have data to determine the extent of hazardous waste contamination, potential costs of remediating hazardous waste sites, and the potential health risks posed by those sites.

Currently, data do not exist to prioritize and manage DoD hazardous waste sites in the ROK based upon extent of contamination or the level of risk. Since DoD policy specifies "...reducing risk to human health and the environment by identifying, evaluating, and where necessary, remediating contamination resulting from past DoD activities," a method is required to obtain these data. Unfortunately, resources required to obtain this data are severely constrained. Thus, the method selected to obtain these data must be both expedient and cost effective, yet provide information adequate to meet decision-maker needs. In this manner, information required to proactively formulate

intelligent policy will be available and constrained resources can be applied in the most environmentally sound and cost-effective manner.

D. Research Objective

The overall objectives of the proposed research are twofold:

1. Present a method and technology alternatives, which are appropriate for use at DoD installations in the ROK, to expeditiously obtain inexpensive site characterization data that can be used for risk assessment as well as refinement of remedial cost estimates, and:

2. Provide a methodology for using the data so obtained to establish the health risk or risk-based corrective action (RBCA) levels of sites.

Specifically the research will focus on answering the following site characterization and risk assessment/RBCA questions:

1. What are the primary sources of contamination, and what primary contaminants are expected to be found in the greatest quantities;

2. What site characterization data are currently available at U.S. installations in the ROK and what additional data are required to support risk assessment/RBCA and remedial cost estimation;

3. What criteria should be used in selecting site characterization technologies for use at U.S. installations in the ROK;

4. What expeditious site characterization technologies are readily available, and can these technologies be utilized at our installations in Korea;

5. What are the costs and corresponding capabilities of these technologies;

6. What risk assessment/RBCA methods are available for employment at our Korean installations;

7. What are the data requirements for applying the various risk assessment/RBCA methods;

8. What are the advantages and disadvantages of the various risk assessment/RBCA methods; and

9. Which risk assessment/RBCA method is most appropriate for application to Korean installations, and what are the criteria that should be utilized in defining "most appropriate."

The research approach will first entail a review and evaluation of relevant site characterization methods, principles, and technologies, risk assessment principles and methods, and their respective advantages and disadvantages. A Multiple Criteria Decision Making (MCDM) methodology will be utilized along with the decision-maker's preference structure to rank the technologies and methods that are most applicable to the unique requirements and constraints of DoD installations in the ROK. Compilation of information on the various site characterization technologies and risk assessment methods will be achieved primarily through comprehensive literature review, and secondarily through interviews and correspondence. Criteria selection and preference structure development to be used in the selection of the preferred or most appropriate characterization technologies and risk assessment methods based upon the conditions in Korea will primarily be accomplished through a comprehensive decision-maker survey, and secondarily through interviews during a site visit to Korea and additional literature review.

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E. Scope and Limitations

The research is limited to evaluation of expedient site characterization technologies and risk assessment methods. Although the data eventually generated from employment of the chosen site characterization technology will support remedial cost estimates, the research effort focusing on cost estimation is being performed separately. In addition, the research will not focus on hazardous waste site remedial alternatives.

Specific limitations are as follows:

1. The site characterization technologies are intended to efficiently and cost-effectively determine, qualitatively, the presence or absence of contamination as well as being able to provide sufficient quantitative data to support risk assessment and remedial cost estimates;

2. Evaluation and selection of site characterization technologies will be limited to those defined as innovative technologies. Emerging technologies, while possibly applicable for use in the future, are currently not readily available for field use; as such, these technologies will be discussed, but they will not be included in the formal MCDM evaluation;

3. The risk assessment/RBCA methods are intended to be used to efficiently determine hazardous waste site health risk or risk-based corrective action levels of sites, which can then be utilized to categorize and prioritize sites. Due to use of relative risk and RBCA methods or selection and evaluation of specific chemicals of concern, the alternative risk assessment/RBCA methods may be limited in their ability to provide complete, chemical-specific magnitudes of risk for all chemicals identified at a site. In

addition, the scope of risk assessment will be limited to the human health risk assessment, and as such will not consider ecological risk assessment;

4. The MCDM method of selecting among site characterization technologies and risk assessment methods is not the lone method of performing this task, but it is the method of choice for this research effort. MCDM helps determine solutions to complex problems based upon the criteria selected for evaluation of alternatives as well as the preference structure of the decision-maker. The decision-maker has a strong influence on the ranking of alternatives through determination of which criteria are most important or best represent the decision at hand as well as how heavily the various criteria are weighted relative to one another.

II. LITERATURE REVIEW

A. Introduction

Expeditious methods for site characterization and risk assessment at DoD hazardous waste sites in the ROK require development of a modern approach, owing to the specifics discussed in the introductory chapter. This modern approach has its roots in the USEPA Brownfields program. The focus of the Brownfields program is to expeditiously investigate, evaluate, and remediate contaminated properties having the potential for economic redevelopment in the short term (Ahert et al, 1996:679). To this end, limited site investigations, risk-based assessments, and focused feasibility studies are being used instead of lengthier traditional studies (Ahert et al, 1996:679). Thus, as a broad generalization, it would appear that the methods that have been developed and used to identify, characterize, assess, and remediate Brownfields sites in the US may be very applicable in addressing DoD hazardous waste sites in the ROK.

More specifically, several tools have been proven effective in expeditiously characterizing and accurately assessing sites. These tools include the accelerated site characterization (ASC) process, development and use of dynamic workplans as a component of the ASC, and recognition of data quality indicators (DQI) and incorporation of data quality objectives (DQO) into dynamic workplan development. ASC takes advantage of innovative technologies, on-site analytical methods, and a dynamic workplan to continually refine the conceptual model of the studied site. The dynamic workplan provides a template outlining how the site will be evaluated, with built-in flexibility and adaptability to meet changing site conditions and decision-maker data needs. Throughout this whole process, DQOs and DQIs provide answers to the questions of what are acceptable data and what are not acceptable data. DQOs and DQIs

are not meant as roadblocks to expeditious characterization and assessment, rather, they are meant to be tools to ensure confidence in data quality – data that will be used to make very important decisions.

Thus, an understanding of the Brownfields program, the ASC process, the dynamic workplan, DQOs and DQIs, innovative characterization technologies, and modern risk assessment methods is necessary for decision-makers to develop environmental strategy with regard to DoD installations in the ROK. Synthesis of this information and appropriate implementation of these tools ensure quality data will be obtained quickly and cheaply, while providing the necessary information to best allocate scarce resources. The discussion to follow addresses these tools. In closing this chapter, the reader will be introduced to the concept of multiple criteria decision-making, and its role in selection of innovative site characterization technologies and modern risk assessment methods.

B. Expeditious Site Characterization

Brownfields Initiative. Personnel at DoD installations in the ROK have routinely performed a variety of activities that historically have lead to environmental contamination. Accidental spills, system leaks, improper disposal and a host of other practices (both intentional and unintentional) have contributed over time to installation contamination. Practices of waste treatment and disposal accepted as standard operating procedure just two decades ago are now recognized as detrimental to the environment.

At present in the US, the USEPA, spearheaded by President Clinton's Brownfields Initiative, has undertaken a new approach to address the reuse of urban industrial sites with known or suspected contamination. The primary characteristics of

the Brownfields redevelopment process include speed, flexibility, compatibility and cost-effectiveness (Cichon, 1997:48). This approach is relevant to this thesis in that the tools and techniques employed in the Brownfields program appear directly applicable to the process of characterizing, assessing risk at, and eventually remediating contaminated sites at DoD installations in the ROK. These DoD installations share many characteristics with the potentially contaminated and poorly characterized urban industrial areas that are the focus of the Brownfields Initiative.

In the U.S., the conventional practice for addressing Superfund sites (and specifically Installation Restoration Program sites for the DoD) has been to engage environmental consultants or in-house technical staff to conduct site assessments, following Superfund investigation models required by federal and state governments (McKenna, 1998:2). These investigations generally utilize conventional sampling and analytical methods that are costly and time-consuming (McKenna, 1998:2). Strategies employed in meeting Brownfields redevelopment initiatives have modified these traditional models in order to expedite the site characterization, contaminant remediation/risk reduction (if required), and the land reuse process. Unlike Superfund, the Brownfields development process is based not only on cleaning up the property and reducing health risk, but reusing the land beneficially (McKenna, 1998:3). With limited availability of vital land resources in the ROK, the DoD is in a similar position with the majority of its potentially contaminated sites. That is, intelligent, cost-effective remediation, acceptable reduction of risk, and beneficial reuse, which are the drivers of the Brownfields Initiative, are directly applicable to DoD installations in the ROK.

In implementing the Brownfields Initiative, state legislative action regarding soil and groundwater cleanup standards allows responsible and non-responsible parties a menu of options, which frequently include the following (Dinsmore, 1996:40):

1. Cleanup to background conditions, with the definition of "background" varying among the states but usually meaning natural and manmade conditions at the site except those attributable to the release of hazardous substances;

2. Cleanup to generic, statewide, numeric standards, in which the state establishes risk assumptions to which the remediating party can make limited modifications. In many states, the generic standards vary according to the proposed site use; and

3. Site-specific, risk-based, and use-based standards, in which the remediating party can opt to undertake an "alternative" analysis of site conditions.

The remediating party thus can choose between accepting a regulator's risk assumptions or defining a site-specific standard based on an empirical risk analysis (Dinsmore, 1996:40). The application of risk- and use-based standards and the methods of obtaining data to determine remedial strategy based on these standards, has direct relevance to DoD decision-makers in the ROK. According to the option chosen by the remediating party, resource requirements will vary, and these requirements will in-turn influence decision-maker preferences.

Time and money are critical drivers in the Brownfields redevelopment process, and thus employment of expedient, cost-effective site characterization technologies becomes crucially important. Few site developers will have the luxury of completing comprehensive remedial site investigations before initiating clean-up activities (Cichon,

1997:48). These and many related issues require a remedial strategy that differs substantially from the conventional, typically fragmented approach long employed by most federal, state and private sector projects (Cichon, 1997:48). Analogously, DoD decision-makers in the ROK also do not have the time, money and other resources required of traditional remedial strategies. Thus, the Brownfields model is a general paradigm that is directly applicable to hazardous waste site characterization and risk assessment strategies at DoD installations in the ROK.

Regardless of when and how clean-up is accomplished, the challenges to any Brownfields program is to clean-up sites quickly and redevelop the land in ways that benefit communities and the local economies (USEPA Road Map, 1997). One key to expedient clean-up and rapid redevelopment is the use of field-based site characterization technologies. In fact, the USEPA's Technology Innovation Office encourages the use of innovative and cost-effective technologies to characterize and clean-up contaminated sites (USEPA Road Map, 1997). Listed in Table 1 are the three EPA-defined technology categories as applied to Brownfields investigations.

Innovative and emerging technologies may hold promise for characterization of DoD hazardous waste sites in the ROK. DoD, USFK, and component service decision-makers must evaluate the technology options for conformance to their needs. During this evaluation, the decision-makers will make trade-offs between the risks of utilizing these innovative and emerging technologies and the benefits to be gained. A primary objective of DoD decision-makers in characterizing suspected or known hazardous waste sites in the ROK is parallel to that of the Brownfields site investigation objective, namely to identify the source, nature and extent of contamination. In order to meet this objective, a

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Table 1. Brownfields Site Characterization Technology Descriptions
(USEPA Road Map, 1997)

Technology Class	Description
Emerging Technology	An innovative technology that is undergoing bench-scale testing, in which a small version of the technology is tested in a laboratory.
Innovative Technology	A technology that has been field-tested and applied to a hazardous waste problem at a site, but lacks a long history of full-scale use. Information about its cost and how well it works may be insufficient to support prediction of its performance under a wide variety of operating conditions.
Established Technology	A technology for which cost and performance information is readily available. Only after a technology has been used at many different sites and the results fully documented is that technology considered established.

proper technology or mix of technologies must be employed to facilitate identification of environmental conditions and meet stated data quality objectives. Table 2 presents a list of potential contaminants or parameters to be monitored along with a listing of assorted innovative field analytical technologies.

DoD (in conjunction with the Army Corps of Engineers (ACE), in many cases) has a major role in the Brownfields program. The Brownfields National Partnership Action Agenda, established May 1997, outlines the roles and responsibilities of federal agencies. In the four phases identified in the Agenda, including community planning, assessment and cleanup, redevelopment support, and sustainable reuse, DoD has the following responsibilities (EPA BNPAA, 1997):

1. Community Planning

    A. DoD will coordinate economic adjustment initiatives in defense impacted communities with Brownfields redevelopment planning efforts; and

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B. DoD/ACE, in cooperation with states, will prepare comprehensive plans for environmental restoration of water resources at Brownfields pilots *;

2. Assessment and Cleanup

   A. DoD will share its Base Realignment and Closure (BRAC) partnering, assessment, and cleanup tools with Brownfields pilots;

   B. DoD will resolve problems associated with transfers of contaminated properties between federal agencies;

   C. DoD/ACE will review and revise internal Civil Works policies and guidance so as to support Brownfields cleanup and restoration;

   D. DoD/ACE will review inventory of Formerly Used Defense Sites (FUDS) and make inventory information available to Brownfields pilots;

   E. DoD/ACE will provide planning assistance to pilot communities *;

   F. DoD/ACE laboratories will share their research and technology with Brownfields pilots to expedite and improve local assessment and cleanup efforts; and

   G. DoD/ACE will share its "area economic data" with Brownfields pilots.

3. Redevelopment Support

   A. DoD will develop model guidelines to streamline the early transfer of federal facilities;

   B. DoD will develop policy options to encourage reuse of Brownfields on DoD property rather than Greenfields;

   C. DoD/ACE will share GIS and other data on Brownfields pilots, within its project study areas, with pilots *; and

D. DoD/ACE will provide market impact studies and cost benefit analysis to Brownfields pilots *.

4. Sustainable Reuse

   A. DoD/ACE will provide appraisal, title and deed restriction services to Brownfields pilots *; and

   B. DoD/ACE will carryout projects for the protection, restoration, and creation of aquatic and ecologically related habitats in connection with the disposal of dredged materials at Brownfields pilots.

Action items marked with a "*" indicate the work will be carried out on a reimbursable basis. While the scope of responsibility for DoD and the ACE is significant, the above-listed items also point toward a store of potential knowledge and expertise that may be tapped to help DoD decision-makers in their efforts to characterize and remediate installations in the ROK.

The Brownfields Initiative had shown a great deal of success since its inception. Listed below is a sampling of successes of the Brownfields redevelopment strategy (Dinsmore, 1996:41):

1. Since October 1993, more than 3,200 remedial actions have been completed in Massachusetts, while the number of sites remediated has risen from some 100 per year to over 500 per year;

2. Since late 1993, more than 180 projects had entered the California program, and as of October 1995, remedial actions had been completed at half of them;

3. As of June 30, 1995, participants in Minnesota's program had achieved cleanups at 75 sites, and 210 additional cleanups were in progress; and

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4. As of June 30, 1995, participants in Oregon's program had completed 34 cleanups, and 22 more were in progress.

While reduction of liability or shared liability schemes, streamlining/reduction of regulatory oversight, and introduction of public sector financial assistance associated with successful Brownfields Initiative implementation do not play the same major role at DoD installations in the ROK as they do at many hazardous waste sites in the US, much information and many lessons learned in this program can be applied to our installations in the ROK. Among these, use of site investigation and site assessment protocols, employment of innovative and emerging field-based technologies, and application of a risk-based corrective action approach all show promise in providing sample "How To" guidance that can be used in developing intelligent and effective remedial strategies.

Accelerated Site Characterization. The need to rapidly and accurately characterize a confirmed or suspected hazardous waste site is critical to DoD decision-makers in the ROK. Accelerated site characterization (ASC) provides a method of collecting and evaluating information pertaining to site geology/hydrogeology, nature and distribution of the chemical(s) of concern, potential exposure pathways, and potential receptors, in one mobilization (ASTM PS 3, 1997:169). The information obtained using the ASC process should be comparable to that obtained using the traditional site characterization process, with the ASC process providing significant savings in resources. The ASC process for collecting site characterization information employs rapid sampling techniques, on-site analytical methods, and on-site interpretation and iteration of field data to refine the conceptual model for understanding site conditions as the characterization proceeds (ASTM PS 3, 1997:169).

Significance and Use. As stated, the unique goal of an ASC is to complete a site characterization in one mobilization. In meeting this goal, the ASC process has the following advantages (ASTM PS 3, 1997:171):

1. Immediate identification of potential risks to human or environmental receptors or potential liabilities, or both;

2. Rapid determination of the need for interim remedial actions, site classification, and prioritization;

3. Rapid sample collection and analysis, near contemporaneous analytical results, and maximum data comparability;

4. Optimization of sample point locations and analytical methods;

5. Greater number of data points for resources expended;

6. Near immediate data availability for accelerating corrective action decisions; and

7. Collection of vertical and horizontal data, allowing for three-dimensional delineation of chemical(s) of concern in soil, soil vapor, or groundwater.

Accelerated Process Concepts. The unique feature of the ASC process is the collection, analysis, and evaluation of the geologic/hydrogeologic and chemical data while on-site. Significant activities performed on-site during an ASC include the following (ASTM PS 3, 1997:172):

1. Interpretation and evaluation of field-generated data as it is collected;

2. Continuous refinement of the conceptual model, or the understanding of site conditions;

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3. Modification of the sampling and analysis program to address any necessary adjustments in the scope of work; and

4. Collection of additional data necessary to complete the characterization. For the purposes of process discussion, the ASC process can be segregated into several distinct steps. These steps include identification of the need for and the type of site characterization (including objective(s) and purpose(s)), review of existing site information, development of a conceptual model, design of a competent data collection and analysis program, collection and analysis of data, evaluation of data and refinement of the conceptual model, termination of data collection, and generation of a report of findings (ASTM PS 3, 1997:172-175). This process and the iterative steps involved in employment of ASC are depicted in Figure 1.

Identification of Site Characterization Objectives and Purpose. The objectives of any environmental site characterization are to understand the site geology/hydrogeology, the nature and extent of the chemicals of concern, and the migration pathways and location of point(s) of exposure (ASTM PS 3, 1997:172). However, the purpose of the site characterization may take many forms and will dictate the priority of the type of specific information to be collected. Typical site characterization purposes include one or more of the following: hazard determination, initial response action, release confirmation, risk determination, corrective action evaluation, regulatory compliance, or real estate transaction (ASTM PS 3, 1997:172). Site characterization needs of DoD decision-makers in the ROK primarily include risk assessment and corrective action evaluation (which includes generating cost estimates for potential corrective actions).

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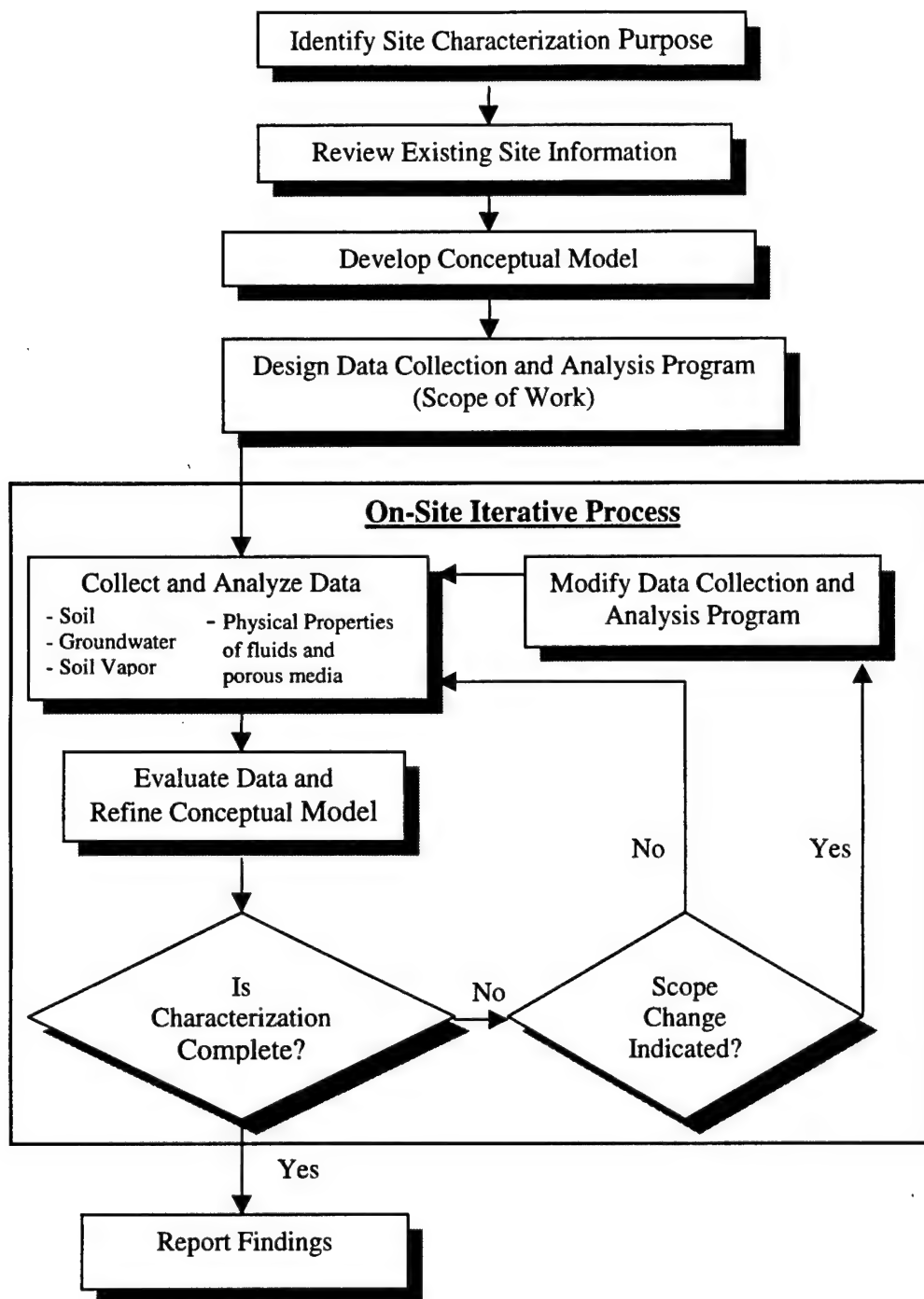
Figure 1. Accelerated Site Characterization Process Flowchart
(ASTM PS 3, 1997:173)

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Existing Site Information Review. A review of existing information is important in the design of a data collection and analysis program, and in the development of the initial conceptual model. Information obtained through a site visit, interviews, and records search include the following (ASTM PS 3, 1997:173):

1. Local and regional geologic/hydrogeologic maps to identify general soil types/regional depth to bedrock, rock type, depth to groundwater, aquifer properties, and so forth;

2. Past and current land use history of the site and adjacent properties (including future land use, if known);

3. Location of potential sources (for example, current and former storage tank systems);

4. Releases, spills and overfill incidents on the site and adjacent properties;

5. Previous or on-going corrective action activities, or both, on-site and on nearby properties (for example, monitoring well installation, soil excavation, groundwater recovery, etc.);

6. Potential human health and environmental receptors, such as public and private dwellings, public and private water supply wells, public recreational facilities, and streams within a given proximity of the site;

7. Potential transport to exposure pathways or specific points of exposure, or both (for example, groundwater, surface water, vapor migration through soils and utility systems, etc.);

8. Other potential sources of off-site chemical(s) of concern; and

9. Site conditions that may affect the health and safety plan.

The site information obtained through information review can be rapidly compiled and utilized to help formulate an intelligent course of action.

Conceptual Model Development. The initial conceptual model is the starting point of the investigation, and is used as a basis for planning field activities (ASTM PS 3, 1997:173). This conceptual model takes all available site information into account and presents the decision-maker with a preliminary "snapshot" of anticipated site conditions. The conceptual model may include the following information (ASTM PS 3, 1997:173):

1. Anticipated locations and depths of subsurface geologic units;

2. Anticipated groundwater depth and flow direction(s) and possible interaction with surface water bodies;

3. Layout of the site;

4. Existing soil and groundwater analytical data and information regarding the location(s) and volume(s) of any leaks, spills or releases;

5. Potential releases in the vicinity of the site (especially up-gradient from the site); and

6. Location of potential receptors.

This information can be summarized using simple graphics such as a large-scale installation map, structure contour maps, and/or groundwater contour maps. These documents should be used on-site and should be updated as the characterization progresses.

Data Collection and Analysis Program Design. The data collection and analysis program is developed based on the initial conceptual model, and development

occurs prior to mobilization. The exact number and location of data collection points are left somewhat flexible, and are determined in the field based upon the actual site conditions. Proper implementation of the data collection program requires that site personnel understand the capabilities and limitations of the sampling tools and field-based analytical methods as well as the timely and proper interpretation of field-generated data (ASTM PS 3, 1997:173). The data collection and analysis program should incorporate the following (ASTM PS 3, 1997:173-174):

1. Purpose of the ASC;

2. Initial conceptual model, including site historical information, geologic/hydrogeologic characteristics of the site, and physical properties of fluids and porous media;

3. Methods to collect and analyze data;

4. General location and number of initial samples and the decision process for locating additional samples;

5. Media to be analyzed;

6. Sample collection and analysis criteria (e.g. depth interval, sampling protocol, chemical(s) of concern, data quality levels, analytical methods, and data validation);

7. Specific qualifications of the on-site field manager and additional site personnel;

8. Site constraints (e.g. structures, canopy, limited space, utilities, property boundaries, depth to bedrock, presence of cobbles, and access constraints);

9. Need for data collection for fate and transport modeling, risk evaluations, or corrective action design;

10. Level of communication between the on-site field manager and staff and the responsible party (e.g. agreement on changes to the scope of work or the data collection and analysis program);

11. Contingency plans based upon reasonably anticipated deviations from expected site conditions, such as shallow bedrock, depth to groundwater, disposal of investigatory wastes, change in equipment requirements, and the appearance or detection of unanticipated chemical(s) of concern; and

12. Determination of the possible need for off-site access.

More discussion will follow in later sections concerning data quality objectives, but the importance of a sound data collection and analysis plan simply cannot be overemphasized, as it is truly a key to an effective ASC.

Data Collection and Analysis. Once a data collection and analysis plan that meets decision-maker requirements and objectives has been completed, actual sample collection and sample analysis can be performed. Sampling tools are a critical component of the ASC process. The selection of sampling tools should be based upon the following (ASTM PS 3, 1997:174):

1. Purpose and anticipated scope of the ASC;

2. Capabilities, limitations, and cost of each tool;

3. Speed by which samples can be obtained;

4. Advantages of using a combination of tools;

5. Site features and layout;

6. Anticipated geologic site conditions;

7. Anticipated chemical(s) of concern and concentration(s); and

8. Disturbance to site operations and neighboring properties.

Sample analysis and interpretation of the resulting data are a vital element of the ASC process. Analysis, according to the ASC process, can be subdivided into two primary categories: 1) geologic/hydrogeologic conditions and physical properties and 2) chemical analysis. Understanding the geology/hydrogeology and physical characteristics of the subsurface is essential to properly evaluate migration potential and to develop an appropriate corrective action plan (ASTM PS 3, 1997:174). Physical and chemical properties and geologic/hydrogeologic characteristics that the decision-maker may require based upon specific site needs are listed in Table 2. This list is not all-inclusive, nor is it implied the decision-maker should attempt to retrieve data for each property or characteristic listed. Rather, data should be collected as needed dependent upon the requirements identified in the conceptual model and stated as requisite in the data collection and analysis plan.

Chemical analysis employs on-site analytical methods that are incorporated into the ASC to analyze soil, soil vapor, groundwater or air, or a combination of these media (ASTM PS 3, 1997:174). On-site analytical methods provide flexibility in determining the location of or the need for additional samples. On-site analytical methods can typically provide more data at lower cost than sending all samples off-site for analysis (ASTM PS 3, 1997:174). Key considerations in selecting field analytical methods include the potential analyte(s) or classes of analytes, the media, site-specific conditions, data quality level, limitations, and (at applicable DoD installations) regulatory acceptance (ASTM PS 3, 1997:174). The analytical method(s) selected will depend on the

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Table 2. Physical and Chemical Properties and Geologic/Hydrogeologic Characteristics (ASTM PS 3, 1997:177-178)

Category	Properties and Characteristics
Fluid Properties (e.g. Liquid, Dissolved, and Vapor-Phase Contaminants)	Density; Viscosity; Interfacial Tension; Solubility; Sorptive Properties; Vapor Transport Properties; Chemical Composition
Fluid-Media Properties	Wettability; Capillary Pressure-Saturation Relations; Moisture Content; Relative Permeabilities (air permeability)
Porous Media Properties	Intrinsic Permeabilities; Porosities (total and effective); Bulk Density; Pore Volume; Hydraulic Conductivity; Grain Size Distribution; Organic Carbon Content; Clay Content (soil classification); Infiltration Rate; Oxygen and Carbon Dioxide Content; Soil pH; Storativity
Local Geology/Hydrogeology	Heterogeneities; Stratigraphy/Lithology/Soil Type; Presence, Type and Relative Abundance of Consolidated Media; Preferential Contaminant Migration Pathways; Depth to Groundwater; Depth to Bedrock/Confining Layer; Aquifer Thickness; Hydraulic Gradient; Groundwater Flow Direction; Dissolved Oxygen; REDOX Potential; Dissolved Metals; Groundwater pH; Hydraulic Conductivity
Contaminant Distribution	Presence of NAPL; Depth to Impacted Soil In Saturated/Unsaturated Zones; Zone of Contamination (depth, base, areal extent of impacted stratum); Areal Extent of Groundwater Plume

chemical(s) of concern or classes of chemicals or indicator compound(s) of interest. Consideration must be given to the targeted sample media and the method's capability of measuring analyte concentrations in that media. The type of data produced and the reliability of results is related to the data quality level of the method used. An example of a data quality classification system applicable to the ASC process is shown in Table 3. As shown in Table 4, several of the field analytical methods are capable of measuring chemical(s) of concern or indicator compounds, or both, at differing data quality levels (ASTM PS 3, 1997:174). When determining what level of data quality is most appropriate, the following is considered (ASTM PS 3, 1997:174):

Table 3. Example ASC Data Quality Classifications (ASTM PS 3,1997:176)

Data Quality Level	Field Applications	Example Methods or Instruments
1 Screening: 1A Qualitative, 1B Semi-Quantitative	Health and Safety; qualitative contaminant screening (DQL 1A); Contaminant Mass Location (DQL 1B)	Portable PID; Portable FID; colorimetric analysis; PID/FID headspace analysis; Infrared; Fluorescence
2 Delineate: Quantitative	Contaminant Plume Delineation; Well Placement; Remediation Process Monitoring	Portable GC; portable IR; immunoassay; USEPA SW-846 field methods; mobile laboratories
3 Clean Zone: Quantitative	Clean Zone Confirmation; Regulatory Monitoring	Standard Laboratory Analysis with SW-846 QA/QC; Mobile Laboratories with Certified Methods
4 Nonstandard: Quantitative	Constituent Surveys of Unknown Contamination; Specialty Analysis	Survey Instrumentation (e.g. GC/MS); Modified Laboratory Methods, with Full QA/QC

1. The quality level selected should be consistent with the purpose and scope of the ASC, and the intended use of the data;

2. A combination of data quality levels along with an appropriate number of data points may be needed to provide a more complete understanding or meet regulatory requirements. Often, many points containing lower quality level data can provide a better understanding of site conditions than fewer data points at a higher data quality level.

3. A lower quality data level is often sufficient to locate source areas or to determine the placement of borings or monitoring wells, or both. Higher data quality levels may be used to determine low concentrations of specific chemicals of concern in soil or groundwater or to locate delineation borings or monitoring wells. Regulatory (if applicable) or decision-maker requirements should be considered with respect to the detection limit of the selected on-site analytical method.

All analytical methods and instruments have limitations that may affect results. These limitations include effects of temperature or humidity, cross-sensitivity issues, masking of certain constituents, inoperability due to certain media characteristics, and

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operational expertise of persons handling the equipment (ASTM PS 3,1997:174). Limitations must be considered when selecting analytical methods or instruments.

Although specific regulatory acceptance is not required for DoD sites in the ROK, decision-makers allocating resources for potential remediation may require certain methods or procedures. The appropriate decision-making authority should be consulted for accepted methods and procedures when an ASC is to be performed to ensure data acceptance.

Method protocol and QA/QC considerations must be included in work plan development for each analytical method employed in the ASC. Each analytical method commonly has a standard protocol established by either the USEPA, a state regulatory agency, an industry consensus group or manufacturer, or has a protocol specifically developed for use on-site (ASTM PS 3,1997:175). Example QA/QC considerations include instrument calibration, review of instrument maintenance log and field logs, blank results, reproducibility, review of deviations, and field standards. These QA/QC considerations, though not necessarily required by law at DoD installations in the ROK, make good sense to incorporate into the site characterization process.

The established data collection and analysis program is implemented to perform an intensive, short-term field investigation. Flexibility is a key component for a successful ASC, therefore, the data collection and analysis program should be used to guide the site characterization to completion (ASTM PS 3,1997:175). As data are collected and analyzed, it may be necessary to adjust the data collection and analysis program to refine the conceptual model and satisfy the purpose of the site characterization (ASTM PS 3,1997:175).

Data Evaluation and Conceptual Model Refinement. Geologic, hydrogeologic and analytical data collected throughout the field investigation are continually interpreted on-site by the field manager and field staff. Compilation of the data onto simple graphics is essential for on-site data interpretation (ASTM PS 3,1997:175). As the investigation proceeds, the graphics are continually revised through incorporation of the latest data. Using the field-generated graphics, the on-site field manager directs the investigation to alleviate data gaps or resolve anomalies, or both. New data are collected, and the investigation proceeds in an iterative, scientific manner until the site geology, hydrogeology, and nature and extent of soil and groundwater contamination are accurately defined (ASTM PS 3,1997:175).

The degree of detail and accuracy of the graphical representation of site conditions varies according to the purpose of the characterization, complexity of the site geology/hydrogeology, and the type and volume of the released contaminant (ASTM PS 3,1997:175). In order to ensure the capture of useful field-generated data, the data must be validated. Considerations for data validation include the following (ASTM PS 3,1997:175):

1. QA/QC results (e.g. replicates, duplicates, multi-point calibration curves, calibration checks, blanks, and so forth);

2. Comparison of higher quality level data to check lower quality level data;

3. Comparisons with results from other media;

4. Comparisons with other chemical(s) of concern or indicator compounds;

5. Comparisons against previous data, if available; and

6. The data should make sense in the context of the site conditions and previously generated data.

Once data has been validated, it can then be used to determine whether data quality requirements and objectives have been met.

Termination of Data Collection. The data collection and evaluation process should continue until the on-site field manager has determined that the site is fully characterized or that constraints prevent complete characterization (ASTM PS 3,1997:175). Typically, the ASC is complete and no further data collection is required when the following have been satisfied (ASTM PS 3,1997:175):

1. The conceptual model of the site geology/hydrogeology, nature and extent of chemicals of concern, and indicator compounds fit the regional geologic/hydrogeologic setting; and

2. The conceptual model of the site generally incorporates/fits all of the site data; and

3. The conceptual model can be used to make accurate predictions; and

4. Sufficient detail and delineation of the chemicals of concern have been achieved to fulfill the requirements of the responsible party/decision-maker; or

5. Constraints prevent collection of any additional data.

Report of Findings. Once fieldwork has been completed, the findings are compiled in a cohesive report and provided to the decision-maker. The report should contain at a minimum: the purpose of the characterization, a statement of objectives, the background data, a description of the data collection and analysis program, a presentation or summary of the data, and QA/QC measures (ASTM PS 3,1997:175). The report may

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then be used to identify the appropriate course of action according to decision-maker priorities and preferences. Possible uses for the report include performance of an evaluation under the risk-based corrective action (RBCA) process, performance of a preliminary remedial cost estimate, and an evaluation of remedial action alternatives. If the data warrant, the report may also be utilized to select and defend the no further action-required decision.

Dynamic Workplans. The ability to rapidly assess the disposition of environmental contaminants at purported or existing hazardous waste sites is an important component of the DoD restoration program. Despite the best efforts of the USEPA and other federal agencies including the Departments of Defense and Energy to validate on-site analytical methods, the use of these methods has not played a significant role in either hazardous waste site assessments or clean-up (Robbat, 1997:1). President Clinton, supported by the USEPA, responded to this deficiency in 1995 with the Environmental Technology Initiative (ETI) (Robbat, 1997:1). Two key objectives identified in the Strategic Plan developed to implement objectives outlined in the ETI were as follows (Robbat, 1997:1):

1) strengthening the capacity of technology developers and users to succeed in environmental innovation and

2) strategically investing EPA funds in the development and commercialization of promising new environmental monitoring, control, and remediation technologies.

Development of the dynamic workplan guidance represents one aspect of the Strategic Plan by incorporating field analytical instrumentation and methods into an adaptive sampling and analysis program for expediting the site characterization process.

This dynamic process should result in faster, better, and hopefully cheaper site characterization and clean-up (Robbat, 1997:1).

Workplan Comparisons. Successful hazardous waste site characterization efforts, while focused on clearly defined goals and objectives, should still retain flexibility and adaptability. Traditional site characterization workplans rely upon pre-specified sampling locations, sample collection schedules and types of analyses performed (Robbat, 1997:2). The traditional site characterization is static in its application and it does not provide a framework for changes in direction based on what is learned in the field (Robbat, 1997:2). Experience has shown that multiple field investigations within the same or subsequent seasons are required to fill data gaps (Robbat, 1997:2).

Dynamic workplans, however, provide an alternative to the traditional approach. The dynamic approach relies upon an adaptive sampling and analysis strategy. Dynamic workplans specify the decision-making logic that will be used in the field to determine which chemical compounds require analysis, where to collect the samples, and when to stop sampling (Robbat, 1997:2). The dynamic workplan evolves as the conceptual model for the site is refined based on the analytical results produced in the field.

Factors to be Considered. When deciding to carry out a dynamic workplan/adaptive sampling and analysis program, the decision-maker should consider the following relevant questions (Robbat, 1997:3-4):

1. Is it possible to assemble a well-rounded core technical team to address site issues?

2. Will the core technical team be in the field for the duration of the investigation? Is the decision-making process well defined and is the authority vested in an appropriate technical team member?

3. Has the action level for field decisions been established as part of the DQOs?

4. Will the project objectives permit screening and semi-quantitative data or will quantitative data only be required to meet DQOs?

5. Has the percentage of samples (recommended to be at least ten percent) to be analyzed in an off-site laboratory for confirmation analysis been addressed? Has the methodology for determining field and laboratory data comparisons been addressed?

6. When selecting the field instrument or method, have measurement selectivity, sensitivity, precision, accuracy, representativeness, and action levels been addressed?

7. Can standard operating procedures and method detection limit studies be completed before mobilization to evaluate matrix interferences that might be associated with a particular field technology?

8. Will data management tools and geostatistical sampling tools be integrated into the field investigation?

9. Is the site accessible for field analytic deployment including mobile laboratories, electrical power, and water, if necessary?

10. Does the length of the project and potential overall cost savings warrant this approach?

Purpose and Objective. Dynamic workplan investigations are site dependent. They include field-based technologies and methods that produce chemical, physical, geological, and hydrogeological information about the site. The data generated

must be of sufficient quality, with respect to measurement precision, accuracy, sensitivity and completeness, to support the objectives of the site characterization or clean-up (Robbat, 1997:4). The dynamic workplan/adaptive sampling and analysis process is intended to lay the foundation for incorporating an iterative process into the static but widely used DQO framework for decision-making planning (Robbat, 1997:4). Proper implementation of the ASC process, incorporating applicable DQO planning objectives and utilizing the dynamic workplan/adaptive sampling and analysis program strategy, is the overall goal of this site characterization methodology.

Process. The dynamic workplan process, as described by Robbat, involves six primary steps. Again, in constructing the dynamic workplan, it is important to determine prior to mobilization what decisions will be made, how these decisions will be made, and who will make them in the field (Robbat, 1997:5).

Step 1 involves selecting the core technical team whose responsibility it will be to prepare the dynamic workplan. The team should possess needed field experience, provide specific discipline expertise, and assist with data management, QA/QC, fate and transport modeling, and health and safety (Robbat, 1997:5). The technical team should be responsible for the following (Robbat, 1997:5):

1. Gathering all available information for the site;

2. Developing an initial "conceptual" model for the site;

3. Identifying the technical objectives and goals to be accomplished;

4. Supervising the field effort and making adjustments to the conceptual model based on the data produced in the field; and

5. Evaluating the conceptual model and decisions made with respect to agreements, treaties, and governing standards.

The core technical team will be responsible for making decisions in the field. At least one member of the technical team should be on-site during execution of field activities, and this person must have a working knowledge of all aspects of the data quality objectives (DQOs). This individual should have daily contact with technical team members, whether via electronic data transfer or other means (Robbat, 1997:5).

Step 2 involves development of the initial conceptual model and decision-making framework. The initial conceptual model contains the best available site information at the start of the project, including (if available) site contamination profile, key site features, geologic/hydrogeologic characteristics, and potential contaminant transport pathways, among others. The conceptual model is dynamic in nature and changes to reflect the increased site knowledge gained from field activities (Robbat, 1997:6).

This initial conceptual model is based upon the information utilized in development of the initial DQOs for the site. The DQO process involves a series of planning steps designed to ensure that the type, quantity and quality of environmental data used in decision-making are appropriate for the intended application. The DQO process will be discussed in detail in a later section. Because several levels of data quality may be appropriate to answer the site-specific scientific and engineering questions that must be addressed, the term sufficient or acceptable data quality is meaningful only when the intended uses for the data are known (Robbat, 1997:7). Therefore, it cannot be overemphasized that cost-effective site investigations are highly

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dependent on anticipating data usage during the life of the characterization-to-cleanup process (Robbat, 1997:7).

Step 3 involves development of standard operating procedures (SOP). SOPs for sample collection and analysis should be produced along with other SOPs required to answer site-specific questions regarding hydrogeology (Robbat, 1997:7). The SOPs should be developed by the core technical team and approved by decision-makers prior to initiating field activities. The field methods incorporated in the SOPs should be "performance based" and provide data of sufficient quality to meet the DQOs (Robbat, 1997:7).

Step 4 involves development of a data management plan. Critical to the success of the dynamic process is the ability to manage and easily use all of the data produced in the field (Robbat, 1997:7). Data integration (chemical, physical, geological, hydrological), sampling, and analysis protocols should be incorporated into an overall data management plan (Robbat, 1997:8). The plan should be established with guidelines and responsibilities defined prior to mobilization for the collection, assimilation, and presentation of the field-generated data.

Step 5 involves development of quality assurance (QA) and quality control (QC) requirements. These requirements relate to the sampling method, analytical procedures, and appropriate QA/QC procedures. QA/QC defines the responsibilities of the technical team and decision-makers, and describes the procedures to be used to monitor conformance with or documentation and justification of departure from the SOPs (Robbat, 1997:8). The overall goal is to ensure that data of known quality have been produced to support the decision-making process.

Step 6 involves preparation of a health and safety plan. This plan should address necessary worker and site monitoring requirements and appropriate health and safety procedures to ensure worker and community safety (Robbat, 1997:8).

Data Quality Objectives. Employment of the ASC process, dynamic work plans, and on-site analytical methods in concert optimizes resource utilization. However, in this versatile, field-based characterization approach, the data obtained must be of sufficient quality to support decision-maker objectives. The DQO process ensures data of sufficient quality and reliability are obtained in order to maximize data value and minimize data cost for the ASC.

Identification of appropriate DQOs is intended to complement the ASC process. DQOs are not intended to place undo burden on the decision-maker and site personnel, instead, they focus effort on when, where, how, and why the environmental data are to be obtained and utilized. In accordance with the ASC process, DQOs should be integrated into the data collection and analysis program design and play a role in determining inputs for data evaluation and conceptual model refinement. A successful site characterization, whether traditional or accelerated, is built upon the foundation of sound DQOs.

Scope. The DQO process is a series of planning steps based on the scientific method that is designed to ensure that the type, quantity and quality of environmental data used in decision-making are appropriate for the intended application (USEPA DQO, 1993:1). The steps comprising the DQO process are illustrated in Figure 2. DQOs are qualitative and quantitative statements that provide pertinent information focused on meeting the following objectives (USEPA DQO, 1993:1):

1. Clarify the study objective;

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2. Define the most appropriate type of data to collect;

3. Determine the most appropriate conditions under which to collect the data;

and

4. Specify acceptable levels of decision errors that will be used as the basis for

establishing the quantity and quality of data needed to support the decision.

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│   │  Identify Inputs to the Decision │
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│   │   Define the Study Boundaries │   │
│   └─────────────────────────────┘    │
│                 ↓                     │
│   ┌─────────────────────────────┐    │
│   │    Develop a Decision Rule   │    │
│   └─────────────────────────────┘    │
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│   ┌─────────────────────────────┐    │
│   │ Specify Limits on Decision Errors │
│   └─────────────────────────────┘    │
│               ↓  ↑                    │
│ ┌───────────────────────────────────┐│
│ │ Optimize the Design for Obtaining Data │
│ └───────────────────────────────────┘│
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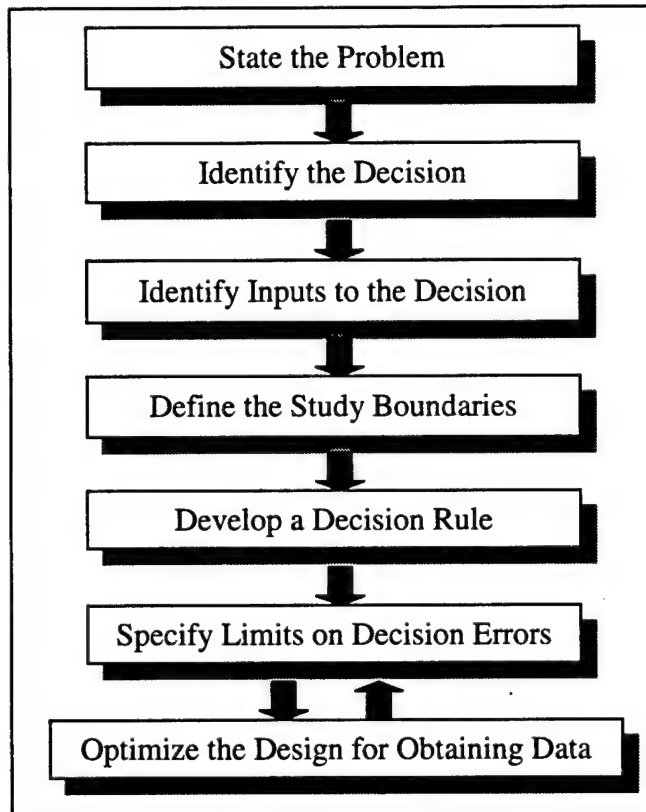
Figure 2. The Data Quality Objectives Process
(USEPA DQO, 1993:6)

The DQO process was developed by the USEPA to help ensure personnel collect

data that support both effective and defensible decision-making. The DQO process is

meant to be both flexible and iterative. Often, especially for more complicated sites, the

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scoping team (DoD decision-maker and staff, on-site manager, and select specialty staff) will need to return to earlier steps to rethink or better focus the objectives and the output desired to reach those objectives. In a manner parallel to the ASC process, these iterations through the earlier steps of the DQO process can lead to a more focused design that can save resources in subsequent field investigation activities (USEPA DQO, 1993:6).

Data Quality Objectives Process Description. The DQO process is a seven step planning procedure that helps identify data characteristics that satisfy the decision-maker's needs. The outputs from the steps of the DQO process are qualitative and quantitative statements about why the data are needed, what the data should represent, and how much uncertainty is tolerable to the data user (Keith, 1996: 128). The following discussion defines the purpose and activities included in each of the seven steps.

State the Problem. The purpose of this step is to summarize the contamination problem that will require new environmental data, and identify the resources available to solve the problem (USEPA DQO, 1993:9). Activities performed include the following (USEPA DQO, 1993:9-12):

1. Identify members of the scoping team;

2. Develop/refine the conceptual site model;

3. Define the exposure pathways and exposure scenarios;

4. Specify available resources; and

5. Write a brief summary of the contamination problem.

Identify the Decision. The purpose of this step is to identify the decision that requires new environmental data to address the contamination problem (USEPA DQO, 1993:13). Activities performed include the following (USEPA DQO, 1993:13-15):

1. Identify the key decision for the current phase or stage of the project;

2. Identify alternative actions that may be taken based upon the findings of the field investigation; and

3. Identify relationships between this decision and any other current or subsequent decisions.

Identify Inputs to the Decision. The purpose of this step is to identify the information needed to support the decision, and specify which inputs require new environmental measurements (USEPA DQO, 1993:17). Activities performed include the following (USEPA DQO, 1993:17-19):

1. Identify the informational inputs needed to resolve the decision;

2. Identify sources for each informational input, and list those inputs that are obtained through environmental measurements;

3. Define the basis for establishing contaminant-specific action levels; and

4. Identify potential sampling approaches and appropriate analytical methods.

Define the Study Boundaries. The purpose of this step is to specify the spatial and temporal scope of the environment that the data must represent to support the decision (USEPA DQO, 1993:21). Activities performed include the following (USEPA DQO, 1993:21-25):

1. Define the geographic areas of the field investigation;

2. Define each environmental medium of concern;

3. Divide each medium into strata having relatively homogeneous

characteristics;

4. Define the scale of decision-making;

5. Determine the time-frame to which the decision applies;

6. Determine when to take samples; and

7. Identify practical constraints that may hinder sample collection (reconsider

previous steps as necessary).

Develop a Decision Rule. The purpose of this step is to develop a logical

"if...then..." statement that defines the conditions that would cause the decision-maker to

choose among alternative actions (USEPA DQO, 1993:27). Activities performed include

the following (USEPA DQO, 1993:27-28):

1. Specify the parameter of interest (such as mean, median, maximum, or

proportion);

2. Specify the action level for the decision; and

3. Combine the outputs of the previous DQO steps into an "if...then..." decision

rule that includes the parameter of interest, the action level, and the alternative actions.

Specify Limits on Decision Errors. The purpose of this step is to specify

the decision-maker's acceptable limits on decision errors, which are used to establish

appropriate performance goals for limiting uncertainty in the data (USEPA DQO,

1993:29). Activities performed include the following (USEPA DQO, 1993:29-36):

1. Determine the possible range of the parameter of interest;

2. Define both types of decision errors and identify the potential consequences of each;

3. Specify a range of possible parameter values where the consequences of decision errors are relatively minor (gray region);

4. Assign probability values to points above and below the action level that reflect the acceptable probability for the occurrence of decision errors; and

5. Check the limits on decision errors to ensure that they accurately reflect the decision-maker's concern about the relative consequences for each type of decision error.

Optimize the Design for Obtaining Data. The purpose of this step is to identify the most resource-effective sampling and analysis design for generating data that are expected to satisfy the DQOs (USEPA DQO, 1993:37). Activities performed include the following (USEPA DQO, 1993:37-44):

1. Review the DQOs and existing environmental data;

2. Develop general sampling and analysis design alternatives;

3. For each design alternative, verify that the DQOs are satisfied;

4. Select the most resource-effective design that satisfies all of the DQOs; and

5. Document the operational details and theoretical assumptions of the selected design in the sampling and analysis (or work) plan.

Data Quality Indicators. Data Quality Indicators (DQIs) are qualitative and quantitative descriptions used in interpreting the degree of acceptability or utility of data (USEPA Guidance, 1998:D-1). While the ASC process prescribes an expedited, field-based approach to sampling and analysis, an understanding of DQIs and a recognition of their effects on data quality are vital for sound decision-making. Utilizing field-based

analytical methods, the characterization process is extremely dynamic, and application of DQI checks to sampling and analysis procedures ensures high quality data are obtained. Given the many ways in which error can arise in environmental sampling, the Quality Assurance (QA) community has developed a set of DQIs that describe the various performance characteristics of a data set. DQIs are commonly described in terms of precision, bias, representativeness, completeness, and comparability (Keith, 1996:121). Commonly accepted definitions for DQIs and typical assessment methods for DQIs are included in Table 4.

Table 4. Common Definitions of Data Quality Indicators (Keith, 1993:123)

Data Quality Indicator	Definition	Typical Expression	Typical Method of Assessment
Precision	A measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions	Standard Deviation, σ	Relative percent difference or relative standard deviation of measurement data
Bias	The systematic or persistent distortion of a measurement process that results in measurements consistently higher (or lower) than the "true" value	Percent reCVery; deviation from reference standard	Spiked sample reCVery; performance evaluation sample result
Representativeness	The degree to which data accurately reflect a characteristic of a population, the parameter variations at a sampling point, a process condition, or an environmental condition		Scientific and statistical evaluation of sampling objectives, population of interest, sampling design, and associated sampling methods
Completeness	A measure of the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under normal conditions	Percent	(100 x number of valid observations ——— (number of planned observations)
Comparability	The degree to which different methods (protocols), data sets, or decisions agree or can be represented as similar. It is a measure of the confidence with which one data set can be compared to another		Scientific and statistical evaluation to determine whether sampling objectives, measurement methods, and data precision are sufficiently equivalent to allow valid comparison

C. Field-Based Site Characterization Technologies

Recent progress in the development of field analytical and site characterization technologies offers potential savings in time and cost compared with traditional technologies (EPA FASCT, 1997:1). Various field analytical and site characterization technologies have been used at Superfund and RCRA sites and at sites with leaking underground storage tanks. In addition, as a result of the EPA's Brownfields Initiative which encourages the productive reuse of abandoned properties that are or are perceived to be contaminated, there is an increasing use of these technologies at such sites (EPA FASCT, 1997:1). Similarly, these technologies show a great deal of promise in conjunction with the ASC process to provide DoD decision-makers in the ROK with data that will support development of an intelligent remediation strategy.

The various field analytical and site characterization technologies will be categorized as either innovative or emerging technologies. Recall innovative technologies are those technologies that have been field-tested and applied at a site, but lack a long history of full-scale use; emerging technologies are those technologies that are currently in development and/or are undergoing bench-scale testing (USEPA Road Map, 1997). In this thesis, innovative technologies will be evaluated by DoD decision-makers for application at potential DoD hazardous waste sites in the ROK, since they are currently available for use. Emerging technologies will be discussed, as they may become available for use in the future, but they will not be evaluated in this thesis.

As previously discussed, it is important to note that many factors can affect the technical feasibility and cost of field analytical and site characterization technologies. Such factors include physical constraints, site layout, data quality requirements, time

constraints, matrix interferences, expected levels of contamination, and other considerations particular to a given site (EPA FASCT, 1997:1). Such factors should be considered in determining whether specific field analytical and site characterization technologies are appropriate for a particular site.

In addition, many of these technologies, while innovative, are not performed in-situ. In those cases where ex-situ analysis is performed, implementation of the technology may require in-situ sample collection through an appropriate method. A summary of sample access and collection tools is provided.

Innovative technologies are described in terms of resource requirements, data quality, and method limitations. These criteria are briefly discussed below, but will be described in greater detail during methodology development. Resource requirements include time and cost factors applicable to the specific site characterization technique. Data quality refers to the type of data produced and the reported accuracy and precision of results. Accuracy will be measured using, r, the correlation between field-based analytical data and confirmatory laboratory data. The coefficient of variation (CV) of replicate samples (and the relative standard deviation (RSD), which when reported in percent is the equivalent of the coefficient of variation) measures the variability relative to the value of the mean, and as such provides an indicator of precision (Devore, 1995:39). These and related statistical parameters are defined in Table 5. Method limitations include method detection limits, sample analysis limitations, and other pertinent physical/chemical constraints.

Table 5. Statistical Terms Used for Innovative Technology Evaluation
(Devore, 1995:39, 496, 510; Leary and Skoog, 1992:A-7, A-17)

Term	Acronym	Definition/Purpose
Coefficient of Variation	CV	Measure of sample precision - equals the variance of the sample divided by the sample mean: $CV = s/x_{bar}$
Sample Correlation Coefficient	r	Measures the degree of linear relationship among variables: $r = S_{xy}/[(\Sigma(x-x_{bar})^2)^{1/2}*(\Sigma(y-y_{bar})^2)^{1/2}]$
Relative Standard Deviation	RSD	Measure of sample precision: $RSD = (s/x_{bar}) * 10^z$, where z commonly equals 2 or 3
Slope of Linear Regression	---	Measure of proportion of the sum of the squares of deviations: $Slope = S_{xy}/S_{xx}$ (1.0 is ideal)
Y-intercept of Linear Regression	---	Measure of systematic error in procedure: $y\text{-intercept} = y_{bar} - slope * x_{bar}$ (0 is ideal)

Sample Access and Collection Tools. The large majority of potential hazardous waste sites in the ROK will require subsurface characterization in order to detect soil and groundwater contamination. The data generated through this effort will support risk assessment, remedial cost estimation, and eventually (if required), remedial alternative feasibility. Hundreds of specific methods and techniques exist for sampling and monitoring the saturated and unsaturated zones at contaminated sites (USEPA CERI, 1993:x).

The FRTR compiled an excellent Table that provides information on the large number of sampling tools that are potentially available for use in site characterization (FRTR, 1998). Table 6, taken from the FRTR report, summarizes the wide variety of sample access and collection tools available to complement those field-based site characterization technologies that require removal of a solid, of a liquid, or of a gas

sample from the subsurface. In addition to Table 6, the reader can obtain detailed information on over 200 subsurface sampling and monitoring techniques in EPA-625-R-93-003, Subsurface Characterization and Monitoring Techniques: A Desk Reference Guide.

Table 6. *Field Sampling and Analysis Matrix* (FRTR, 1998)

FIELD SAMPLING AND ANALYSIS MATRIX: FIELD SAMPLING AND COLLECTION TECHNIQUES											
Most commonly used field techniques from Subsurface Characterization and Monitoring Techniques EPA 625-R-93-003 See Legend below for explanation. **Technique / Instrumentation**	Analytes	Soil	Groundwater	Surface Water	Gas / Air	Maximum Depth	Production Rate	Investigation Derived Waste Volume	Technology Status	Certification / Validation	Relative Cost / Sample
3 ACCESS TOOLS											
3.1 Drilling Methods - Unconsolidated Formations											
3.1.1 *Hollow-Stem Auger*	All	■	●	NA	△	●	●	△	III	No	●
3.1.2 Direct Mud Rotary	All	●	△	NA	△	■	●	△	III	No	●
3.1.3 Directional Drilling	All	●	●	NA	△	●	●	△	III	No	△
3.1.4 Solid Flight and Bucket Augers	All	■	△	NA	△	●	●	△	III	No	●
3.1.5 Jetting Methods	2, 4-6, 10, 11	△	△	NA	△	●	■	△	III	No	■
3.1.6 Sonic Drilling	All	■	●	NA	△	■	■	■	II	No	△
3.2 Drilling Methods - Consolidated Formations											
3.2.1 Direct Air Rotary with Rotary Bit / Downhole Hammer	2, 4-6, 10, 11	■	●	NA	△	■	●	△	III	No	●
3.2.2 *Cable Tool*	2, 4-6, 10, 11	■	●	NA	△	■	△	●	III	No	●
3.2.3 Rotary Diamond Drilling	2, 4-6, 10, 11	■	●	NA	△	■	△	△	III	No	△
3.3 Drive Methods											
3.3.1 Cone Penetrometer	All	■	■	NA	■	●	■	■	III	No	●
3.3.2 Direct Push Sampler	All	■	●	NA	●	●	■	■	II	No	■
3.4 Sampling Installations for Portable Samplers											
3.4.1 Driven Wells	All	NA	■	NA	●	●	■	■	III	No	■
3.4.2 *Single Riser / Limited Interval Wells*	All	NA	■	NA	●	●	■	△	III	No	●
3.4.3 Nested Wells / Single Borehole	All	NA	■	NA	●	●	△	△	II	No	●
3.4.4 Nested Wells / Multiple Boreholes	All	NA	■	NA	●	●	△	△	II	No	●
3.5 Portable *In-Situ* Ground Water Samplers / Sensors											
3.5.1 Direct Drive Samplers	All	NA	■	■	●	●	●	■	II	No	■
3.5.2 Passive Multilayer Samplers	1, 3	NA	■	NA	■	●	●	■	II	No	■

Table 6. Field Sampling and Analysis Matrix, (Cont.) (FRTR, 1998).

FIELD SAMPLING AND ANALYSIS MATRIX: FIELD SAMPLING AND COLLECTION TECHNIQUES

Most commonly used field techniques from Subsurface Characterization and Monitoring Techniques EPA 625-R-93-003 See Legend below for explanation. **Technique / Instrumentation**	Analytes	Soil	Groundwater	Surface Water	Gas / Air	Maximum Depth	Production Rate	Investigation Derived Waste Volume	Technology Status	Certification / Validation	Relative Cost / Sample
3.6 Fixed *In-Situ* Samplers											
3.6.1 Multilevel Capsule Samplers	All	NA	■	NA	●	●	●	●	II	No	●
3.6.2 Multiple-Port Casings	All	NA	■	NA	●	●	●	●	II	No	■
3.6.3 Passive Multilayer Samplers	1, 3	NA	■	NA	■	●	●	■	II	No	■
3.7 Destructive Sampling Methods											
3.7.1 Coring and Extraction	All	NA	■	NA	●	●	●	●	II	No	■
3.7.2 *Temporary Installations*	All	NA	■	NA	●	●	●	●	III	No	■
4 COLLECTION TOOLS											
4.1 Hand-Held Methods											
4.1.1 *Scoops, Spoons, and Shovels*	All	■	NA	NA	NA	△	■	■	III	No	■
4.1.2 Augers	All	■	△	NA	△	△	■	■	III	No	■
4.1.3 Tubes	All	■	NA	NA	NA	△	■	■	III	No	■
4.2 Power-Driven Soil Samplers											
4.2.1 *Split and Solid Barrel*	All	■	NA	NA	NA	△	■	■	III	No	■
4.2.2 Rotating Core	2, 4-6, 10, 11	■	NA	NA	NA	△	●	●	II	No	●
4.2.3 *Thin-Wall Open Tube*	All	■	NA	NA	NA	△	■	■	III	No	●
4.2.4 Thin-Wall Piston / Specialized Thin Wall	All	■	NA	NA	NA	△	■	■	III	No	●
4.3 Portable Positive Displacement											
4.3.1 *Bladder Pump*	All	NA	■	■	NA	■	■	●	III	No	●
4.3.2 Gear Pump	All	NA	■	■	NA	●	●	●	I	No	●
4.3.3 Submersible Helical Rotor Pump	All	NA	■	■	NA	●	●	●	I	No	△
4.3.4 Gas-Driven Displacement Pumps	All	NA	■	■	NA	●	●	●	III	No	■
4.3.5 Gas-Driven Piston Pumps	All	NA	■	■	NA	■	●	●	II	No	△

Table 6. Field Sampling and Analysis Matrix, (Cont.) (FRTR, 1998).

FIELD SAMPLING AND ANALYSIS MATRIX: FIELD SAMPLING AND COLLECTION TECHNIQUES											
Most commonly used field techniques from Subsurface Characterization and Monitoring Techniques EPA 625-R-93-003 See Legend below for explanation. **Technique / Instrumentation**	Analytes	Soil	Groundwater	Surface Water	Gas / Air	Maximum Depth	Production Rate	Investigation Derived Waste Volume	Technology Status	Certification / Validation	Relative Cost / Sample
4.4 Other Portable Ground Water Sampling Pumps											
4.4.1 *Suction-Lift Pumps (peristaltic)*	All	NA	■	■	NA	△	●	●	III	No	■
4.4.2 Submersible Centrifugal Pump	All	NA	■	■	NA	■	●	●	III	No	△
4.4.3 Inertial-Lift Pumps	All	NA	■	■	NA	●	●	●	II	No	■
4.5 Portable Grab Samplers											
4.5.1 *Bailer*	All	NA	■	■	NA	■	●	△	III	No	■
4.5.2 Pneumatic Depth-Specific Samplers	All	NA	■	■	NA	■	●	■	II	No	●
4.5.3 Mechanical depth-Specific Samplers	All	NA	■	■	NA	■	●	△	III	No	■
4.6 Extractive Collection Methods											
4.6.1 Soil Water Extraction	All	■	△	△	NA	●	△	■	II	No	●
4.6.2 Sorbent Devices	All	NA	■	■	■	NA	●	■	III	No	■
4.6.3 Biological Indicators	All	■	■	■	■	NA	△	●	II	No	●
4.7 Gas / Air Collection Methods											
4.7.1 Soil Gas Sampling (static)	1, 3	NA	NA	NA	■	△	●	■	III	No	■
4.7.2 Soil Gas Probes	1, 3	NA	NA	NA	■	●	■	■	III	No	■
4.7.3 Air Sampling Devices	1, 3	NA	NA	NA	■	NA	●	■	III	No	NA
5 EXTRACTION METHODS											
5.1 *Solvent Extraction*	1-7, 10, 11	■	●	●	NA	NA	●	△	II	No	●
5.2 Thermal Digestion	7-9	■	■	■	NA	NA	■	●	II	No	●
5.3 Thermal Extraction / Desorption	2, 4, 5	■	■	■	NA	NA	■	●	II	No	●
5.4 *Purge and Trap*	1, 3	■	■	■	NA	NA	■	●	III	No	●
5.5 *Headspace*	1, 3	●	●	●	■	NA	■	●	III	No	■
5.6 Supercritical Fluid Extraction	2, 4, 5, 10	■	●	●	NA	NA	■	●	I	No	△
5.7 Membrane Extraction	1, 3	NA	■	■	■	NA	■	■	I	No	●
5.8 Sorbent Extraction	1-10	NA	■	■	■	NA	■	■	II	No	■

Table 6. Field Sampling and Analysis Matrix (Cont.) (FRTR, 1998).

Legend

Media	■	Minimum impact	●	Moderate impact	Δ	Maximum impact
	N A	Not applicable				
Maximum Depth	■	100 feet plus	●	Up to 100 feet	Δ	Up to 25 feet
Production Rate	■	Available quickly	●	Available im short amount of time	Δ	Available after an extended wait
Investigation Derived Waste Volume	■	Small	●	Medium	Δ	Large
Technology Status	III	Commercially available and routinely used field technology				
	II	Commercially available technology with moderate field experience				
	I	Commercially available technology with limited field experience				
Certification / Validation	Y es	Technology has participated in CalEPA certification and/or CSCT verification program				
	N o	Technology has not participated in CalEPA certification and/or CSCT verification program				
Relative Cost per Sample	■	Least expensive	●	Mid-range expensive	Δ	Most expensive

Analytes

1- Non-halogenated volatile organics

2- Non-halogenated semivolatile organics

3- Halogenated volatile organics

4- Halogenated semivolatile organics

5- Polynuclear Aromatic Hydrocarbons (PAHs)

6- Pesticides / Herbicides

7- Metals

8- Radionuclides

9- Other inorganics (asbestos, cyanide, fluorine)

10- Explosives

11- Total Petroleum Hydrocarbons

12- Specific analyte (named in matrix)

Innovative Site Characterization Technologies. The selection of specific innovative site characterization technologies that will be evaluated for application at DoD installations in the ROK includes the following technologies: immunoassay, x-ray fluorescence, gas chromatography with detector, anodic-stripping voltammetry, cone penetrometer mounted sensor systems, biosensors, graphite furnace atomic absorption, flame ionization detector, fiber-optic chemical sensor, photoionization detector, and colorimetric indicators. This listing was developed after a comprehensive search of all technologies that would be potentially applicable to characterize DoD installations in the ROK.

Immunoassay. Immunoassay is an analytical technique that takes advantage of the ability of antibodies to selectively bind to a target analyte in a sample matrix, such as soil or water (NHSRC, 1998:M1-52). Antibodies specific to the target analyte are commonly coated onto a small test tube, microwell, magnetic particles, or latex particles. A limited number of antibody binding sites exist within the tube or on the particles. After the target analyte is extracted from the sample matrix and diluted and/or filtered as required, the extract (from solid matrix) or dilutant (from aqueous solution) and an enzyme conjugate (e.g. horseradish peroxidase) are added to the apparatus containing the antibodies. The target analyte in the sample competes with a known concentration of enzyme conjugate for a limited number of antibody binding sites. According to the Law of Mass Action, the greater the concentration of analyte present in the sample, the greater the amount of enzyme conjugate it will displace from the antibody binding sites (NHSRC, 1998:M1-53). After removal of excess enzyme conjugate and performance of required physical and chemical sample preparations, an enzyme substrate

(e.g. hydrogen peroxide) and a chromagen are added to the apparatus containing the antibody, analyte, and enzyme conjugate in order to cause a specific color formation. After a specified amount of time, a stop solution (e.g. sulfuric acid) is added to the apparatus to prevent additional color formation. Since the amount of bound enzyme conjugate determines the amount of color, the degree of coloration in the sample is inversely proportional to sample analyte concentration (NHSRC, 1998:M1-54). The degree of coloration can be utilized in conjunction with visual identification techniques or spectrophotometric instruments to produce qualitative or quantitative results, respectively (NHSRC, 1998:M1-55).

Resource Requirements. The immunoassay test is an analytical technique, and as such, requires a sample collection method to obtain the soil or water sample. Potential sample collection devices are listed in the sample access and collection tools section. Resource requirements associated with the particular sample collection method must be included in determining resource requirements for this field analysis technique.

A typical soil collection and extraction kit will contain enough materials to analyze four to twenty soil samples, with the typical cost ranging from $20 to $40 per sample (NHSRC, 1998:M1-71). Likewise, a typical water analysis kit will contain enough materials to analyze four to twenty soil samples, with the typical cost ranging from $10 to $30 per sample depending on the target analyte(s) and kit manufacturer (NHSRC, 1998:M1-71).

Analysis time requirements vary between approximately 30 minutes and 2 hours (NHSRC, 1998:M1-65). In this time, a batch of 20 to 25 samples can be analyzed

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together. Common throughput rates are 50 to 60 samples per day for water matrices and 30 to 50 samples per day for soil matrices (NHSRC, 1998:M1-65). Actual throughput rates depend on several factors, including the following (NHSRC, 1998:M1-65): 1) the experience of the operator, 2) the size of the batches of samples analyzed together, 3) the exact brand of the immunoassay test kit, 4) the number of dilutions required if using a quantitative test kit, and 5) the number of quality control samples analyzed with the investigative samples.

Data Quality. The immunoassay analysis is capable of providing semi-quantitative to quantitative data depending upon the analyte(s), the test kit, the sample matrix, and the quantitation method. Many factors affect the data quality of this analytical technique. Consistency is especially critical for all the timed steps and with the user's pipetting technique (NHSRC, 19987:M1-62). Accuracy can be greatly improved through following procedures to avoid cross-contamination and through the use of method blanks, through the use of calibration standards and matrix spikes, and through the use of performance evaluation standards (NHSRC, 1998:M1-62,M1-63). Precision can be improved through the use of duplicate analyses.

A PCB Superfund Innovative Technology Evaluation (SITE) demonstration on semi-quantitative kits was performed using two different calibration standards (NHSRC, 1998:M1-68). In the first, 52 soil and water samples were analyzed and produced 28 correct results, 24 false positives, and no false negatives, in comparison to confirmatory lab samples. In the second test, 94 soil and water samples were analyzed, producing 75 correct results, 19 false positives, and no false negatives. Regression analysis indicated good correlation between the two data sets and the confirmatory lab results ($r \sim .87$,

respectively), with the recommendation that 10 to 20 percent of soil samples from the investigation be sent off-site to correct the results for a better match to the confirmatory lab results (NHSRC, 1998:M1-69).

Similarly, several PCP SITE demonstrations were performed (NHSRC, 1998:M1-69). Accuracy rates for the semi-quantitative test kit was 73 percent (remaining 27 percent included 18 percent false positives and 9 percent false negatives). The false negatives occurred in samples having analyte concentrations much less than prescribed action levels (in this case, < 5 mg/kg). In a separate demonstration, PCP-contaminated soil and water samples were analyzed, and correlation between the immunoassay and lab results for 19 water samples was .90, while for 90 soil samples the correlation was .95 (NHSRC, 1998:M1-69).

A demonstration of immunoassay analysis for benzene, toluene and xylene isomers (BTX), included 79 water samples from four separate monitoring well fields (EPA EMSL, 1993:1). The report concluded that samples with BTX concentrations above 100 ppb were accurately identified, while the technique was not robust enough to accurately deal with samples in the 25 to 100 ppb range (EPA EMSL, 1993:2).

In a test for pesticide detection, namely acetochlor, 29 triplicate measurements were made on each of two prepared concentrations (EPA OPP, 1995). At a standard concentration of 0.1 ppb, overall mean concentration determined from the immunoassay was 0.16 ppb, while at a standard concentration of 1.0 ppb, the overall mean concentration determined from the immunoassay was 1.06 ppb.

Precision (as well as accuracy) in the immunoassay analysis is a function of extraction efficiency. Extraction efficiency is influenced by the analyte, extractant,

matrix, extraction time, and extraction technique. Juracek and Thurman provided a comparison of immunoassay and GC/MS for trace atrazine content in groundwater (Juracek and Thurman, 1994:1080-1089). A comparison of 20 original samples with 20 duplicate samples revealed all deviations for the immunoassay analysis within +/- 10 percent (at the .5 µg/kg level). In their study, Hottenstein and others concluded the precision of the immunoassay for detecting PCP contamination in water was good, with a coefficient of variation (CV) of less than 13 percent (Hottenstein et al, 1995:2756). In his study of PCB detection through immunoassay analysis, Baek found that only small differences in spectrophotometer transmittances of duplicate assays indicated good reproducibility of the tests (Baek, 1993:850). In their study of pesticides (acetochlor), the EPA reported less precise results (EPA OPP, 195). Assay of the 0.1 ppb standard produced a CVs ranging from 10 to 23 percent. Assay of the 1.0 ppb standard produced CVs ranging from 8 to 35 percent.

Method Limitations. Method limitations for the immunoassay analysis are tied to analytes and detection limits, sample matrix and analyte extraction efficiency, and kit support requirements. As well, to utilize this method of sample analysis, the sample must be obtained through one of the described field collection procedures and prepared (if required) according to kit manufacturer instructions. Method detection limits proposed by NHSRC are shown in Table 7.

The detection limits for the target analytes will vary depending on the complexity of the matrix, interferences, and the manufacturer of the test kit (NHSRC, 1998:M1-57). Specificity of the method depend on the type of kit utilized. A kit for TPH would key on aromatics and would not be specific to a single PAH. However, kits can be obtained to

identify and quantify individual compounds. Hottenstein and others found that the

immunoassay method demonstrated low cross-reactivity and that the analyses were

unaffected by the presence of numerous organic and inorganic compounds in the sample

Table 7. Immunoassay Analytes and Detection Limits (NHSRC, 1998:1-56)

Compounds	Soil	Water
TPH	2 to 150 ppm	0.1 to 0.5 ppm
BTEX	1 to 5 ppm	10 to 500 ppb
PAHs	0.2 to 25 ppm	1 to 500 ppb
Pesticides	1 to 100 ppb	50 ppt to 10 ppb
PCBs	0.1 to 1.0 ppm	Less than 1.0 ppb
PCP	0.1 to 0.5 ppm	0.1 to 5 ppb
Explosives	0.2 to 1.0 ppm	0.5 to 5 ppb

matrix (Hottenstein et al, 1995:2756-2757). Similarly, Baek confirmed that the

specificity of the immunoassay was high with low cross-reactivity (Baek, 1993:850).

However, NHSRC cautions that many quantitative PAH test kits produced a high degree

of false positives, and some quantitative results being an order of magnitude higher than

confirmatory laboratory samples (NHSRC, 1998:M1-70). NHSRC also noted that semi-

quantitative TPH test kits produced false negatives, since the kits are primarily designed

to respond to lighter aromatic compounds in the petroleum products (which may not be

appreciably present in weathered or heavy petroleum products) (NHSRC, 1998:M1-70).

Other limitations noted by NHSRC include the following (NHSRC, 1998:M1-72):

1. In order for immunoassay test kits to be used efficiently and effectively, prior knowledge of analytes and potential interferences is necessary;

2. The requirement to refrigerate reagents will add to logistical needs;

3. If multiple similar compounds are found at a site, and analyte-specific kits are not being utilized, it may be difficult to accurately quantify the individual compounds due to interferences between them causing false positives;

4. If data quality objectives for a project require quantitative data, then semi-quantitative test kits will not be appropriate.

X-Ray Fluorescence. X-ray spectroscopy is based upon measurement of emission, absorption, scattering, fluorescence, and diffraction of electromagnetic radiation (Leary and Skoog, 1992:357). The primary technique of interest in field-based ASC application is the measurement of fluorescence. X-rays are defined as short-wavelength electromagnetic radiation produced by the deceleration of high energy electrons or by transitions involving electrons in the inner orbitals of atoms (Leary and Skoog, 1992:357). For analytic purposes, X-rays are produced in three ways, namely 1) by bombardment of a metal target with a beam of high energy electrons, 2) by exposure of a substance to a primary beam of X-rays in order to generate a secondary beam of X-ray fluorescence, and 3) by employment of a radioactive source whose decay results in X-ray emissions (Leary and Skoog, 1992:357). The overwhelming majority of field-based XRF analyzers utilize the third method above, primarily to enhance portability.

For an element bombarded with photons of sufficient energy, electrons from atomic sub-shells may be excited to unfilled orbital levels (Leary and Skoog, 1992:358).

The element will regain its initial unexcited state as an electron falls to the lower, vacated energy level. This de-excitation may result in characteristic X-ray emission.

For a qualitative analysis, the wavelength of emitted peaks in the spectrum can be compared to known peak wavelengths, and element presence or absence determined (Leary and Skoog, 1992:375). For quantitative analysis, a signal processor first separates the emissions data into various channels. The net counts per channel in conjunction with peak comparison to a standard peak location chart, helps determine the type and quantity of elements present in the sample (Leary and Skoog, 1992:376-377).

Resource Requirements. Costs reported by EPA for 39 sites ranged from $17 per sample (350 samples analyzed) for site characterization work to $146 per sample (954 multi-element samples analyzed over four-month period) for restoration monitoring (EPA FASCT, 1997:43-50). The above data range included both in-situ and ex-situ analysis. New equipment rental costs reported ranged from $1,000 per week to $6,000 per month (EPA FASCT, 1997:43-50).

Sample throughput rates ranged from 12 samples per hour to 50 samples per day (EPA FASCT, 1997:43-50). The range of sample throughput is directly affected by the sample collection method, the amount of sample preparation required, the number of analytes, and the analysis method (in-situ versus ex-situ). For in-situ operation, the window of the probe is placed in direct contact with the surface to be analyzed. Since analysis in this mode can be quite rapid (often, less than one minute) and heterogeneity can be a concern, it is typical to take three to four measurements in a small area and average the resulting concentrations (NHSRC, 1998:M2-10). This may require three to six minutes per "sample." For ex-situ operation, sample preparation, including drying,

grinding, and emplacing the sample may be required. Sample analysis time can range from minutes to hours per sample.

Data Quality. The field-based XRF is capable of producing qualitative and quantitative data. Example applications include identification of composite materials, determination of inorganic constituents of petroleum products (such as vanadium), and quantification of heavy metals in soil (such as lead). Semi-quantitative data can be produced through repeated in-situ measurements or through ex-situ measurements without the complete use of calibration standards. Quantitative data can be produced from ex-situ measurements incorporating the use of calibration standards and sample preparation protocols.

Piorek found that in the majority of reported cases, the accuracy between the XRF and confirmatory laboratory method was quite good, with a correlation coefficient (r), greater than or equal to 0.90 (Piorek, 1994:284). Piorek also cited a lead study conducted in Colorado in 1991 in which over 3,700 soil samples were collected and analyzed. In this study, the accuracy of the field-based XRF produced an r of 0.92 (Piorek, 1994:284).

Bernick and others utilized two field portable XRF instruments to analyze 12 different waste streams containing varying concentrations of inorganic analytes. The number of observations ranged from 7 to 261, and the analytes included lead, nickel, cadmium, barium, zinc, and chromium. Accuracy was quite good, from a low r of 0.80 for lead in buried scrap metal waste piles to a high r of 1.00 for cadmium in nickel-cadmium battery production waste (Bernick et al, 1995:107-108).

During an EPA SITE demonstration, seven field-based XRF instruments were utilized to evaluate over 300 samples from two sites. Contaminants included arsenic,

copper, lead, zinc, chromium, and barium. In comparing field-generated data to confirmatory lab data, r was 0.90 or greater for the first four metals listed above for all instruments, while r was 0.70 or greater for chromium and barium for all instruments (NHSRC, 1997:M2-26).

The study performed by Bernick and others demonstrated reasonable precision of the field-based XRF. The CV ranged from a low of 3.4 percent for lead in chromium plating waste to a high of 24.4 percent for chromium in chromium tanning waste (Bernick et al, 1995:106-107).

Performing replicate measurements on standards is another means of assessing precision for the field-based XRF. Calculating a relative standard deviation (RSD) for the replicate measurements assesses the precision. The acceptable range of precision for the field- based XRF is as follows: RSD values should be less than 20 percent for most analytes except chromium, which should be less than 30 percent (NHSRC, 1998:M2-26).

In the EPA SITE study utilizing the field-based XRF mentioned above, precision of the seven instruments was good, with RSD values below ten percent for all metals except chromium. RSD values ranged from 1.5 for iron to 25.8 for chromium (NHSRC, 1998:M2-24).

Method Limitations. The FRTR reports detection limits of 10-100 ppm in soil and 0.5 to 10 ppm for water, assuming metals are filtered and the filter subsequently dried prior to analysis (FRTR, 1998). Field-based XRF detection limits range from 20 to 1,000 ppm for the various analytes, depending upon vendor, unit type, sample quality, and element analyzed (FRTR, 1998). NHSRC reports that with the exception of chromium, the method detection limits for most analytes are in the range of

40 to 200 mg/kg (NHSRC, 1998:M2-21). Piorek reported typical detection limits in soil of 50 to 100 mg/kg (Piorek, 1994:285).

Interferences from physical and chemical matrix effects can affect sample results. Physical matrix effects result from variations in the physical character of the sample, such as particle size, uniformity, homogeneity, and surface condition, and commonly mask true analyte concentrations (NHSRC, 1998:M2-16). Chemical matrix effects can occur as X-ray absorption and enhancement phenomena, resulting in under- or over-estimates of analyte concentrations (NHSRC, 1998:M2-16). In addition, moisture content can effect or prevent X-ray penetration into the sample, masking analyte concentrations.

An X-ray source can excite characteristic X-rays from an element only if the source energy is greater than the absorption edge energy for the particular line of the element (NHSRC, 1998:M2-8). Thus, the source has to be selected to ensure excitation of the analyte. If the energy difference between two peaks of the emissions spectrum is less than the resolution of the detector, then the detector will not be able to fully resolve the peaks (NHSRC, 1998:M2-17). This could result in analytes being missed due to overlap of peaks or could create the appearance of greater analyte concentration in the sample than is truly present.

In order to operate some of the field-based XRF instruments, due to radiation source permitting, training, and handling requirements, a specific license is required (NHSRC, 1998:M2-30). As well, instruments having a silicon/lithium detector will require liquid nitrogen and a dewar to hold the liquid nitrogen, creating potential logistical limitations (NHSRC, 1998:M2-30).

Gas Chromatography. The most widely used means of performing analytical separations is chromatography (Leary and Skoog, 1992:579). Applications continue to expand to meet the growing need by scientists for better methods of characterizing complex mixtures.

In all chromatographic separations the sample is dissolved in a mobile phase, which may be a gas, a liquid, or a supercritical fluid (Leary and Skoog, 1992:579). In gas chromatography (GC), the mobile phase is a gas (e.g. helium gas). This mobile phase is then forced through an immiscible stationary phase, which is fixed in-place in a column or on a solid surface. The two phases are chosen so that the components of the sample distribute themselves between the mobile and stationary phase to varying degrees. Those components that are strongly retained by the stationary phase move only slowly with the mobile phase. In contrast, components that are weakly held by the stationary phase travel rapidly. As a consequence of these differences in mobility, sample components separate into discrete bands that can be analyzed qualitatively and/or quantitatively (Leary and Skoog, 1992:580).

A chromatogram provides only a single piece of qualitative information about each species in a sample – its retention time or its position on the stationary phase after a certain elution period (Leary and Skoog, 1992:599). Quantitative information can be derived from the chromatogram. Quantitative column chromatography is based upon a comparison of either the height or area of the analyte peak(s) with that of one or more standards (Leary and Skoog, 1992:580). Still, the amount of information obtained by chromatography is small compared with the information that can be obtained by supplementing chromatography with spectroscopic analysis such infrared (IR), electron

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capture (EC), nuclear magnetic resonance (NMR), or mass spectrometry (MS). Thus, chromatography is often used as a vital precursor to spectroscopic analyses (Leary and Skoog, 1992:599).

MS is currently one method commonly employed with GC in field-based site characterization technologies. A mass spectrum is obtained by converting components of a sample into rapidly moving gaseous ions and separating them on the basis of their mass-to-charge ratios (Leary and Skoog, 1992:420). The transition from sample to gaseous ions is commonly accomplished by bombarding the sample with electrons, ions, molecules or photons or alternatively by thermal or electrical energy (Leary and Skoog, 1992:422). In quantifying analytes of interest, a mass spectrometer contains a detector that converts the beam of ions into an electrical signal that can be processed and displayed to provide desired data. MS is capable of providing information about the qualitative and quantitative composition of both inorganic and organic analytes in complex mixtures, the structures of a wide variety of complex molecular species, isotopic ratios of atoms in samples, and the structure and composition of solid surfaces (Leary and Skoog, 1992:420).

Resource Requirements. Cost reported by EPA for GC analysis (with and without a supplemental detector, as applicable) ranged from $35 per sample to $100 per sample depending upon complexity of analyte mixture, matrix type and extraction time, and data use requirements (EPA FASCT, 1997:30-35). Rental costs for a portable GC and supplemental detector ranged from $1,500 per week to $3,000 per month, with an additional $3,000 to $5,000 per month required for expendable supplies (this reflects 400 to 500 samples) (EPA FASCT, 1997:30-35).

Sample throughput rates reported by EPA for 24 sites ranged from two soil samples per hour to forty soil samples per day, depending upon extraction requirements, analyte mixture complexity, and operator experience and efficiency (EPA FASCT, 1997:30-35). NHSRC reports that analytical times for volatile organic compounds (VOC) should be less than 10 minutes per sample (NHSRC, 1998:M1-87). Kesners and Matz reported a four-minute extraction time for aqueous organic contaminants and an additional five to ten minutes for on-site analysis (Kesners and Matz, 1993:2371).

Data Quality. A GC alone can be utilized to produce qualitative to semi-quantitative data. Qualitative data is produced using a peak identification algorithm in conjunction with system parameters such as the column type, carrier gas flow rate, etc. Semi-quantitative data can be produced using standards in conjunction with a peak height/area algorithm. A GC/MS (or GC plus detector) system can either be used to provide qualitative to semi-quantitative data in a survey mode to quantitative data in an analytical or selective ion (in the case of MS) mode (NHSRC, 1998:M1-87).

Accuracy of the field GC/MS (or GC plus detector) is checked by protocol through establishing a calibration curve, and utilizing daily medium level standard checks, method blanks, performance evaluation samples, and spiked matrix samples (as required) (NHSRC, 1998:M1-91). Aelion and others utilized GC techniques to monitor VOC (primarily BTEX) concentrations in groundwater, soil vapor extraction (SVE) system exhaust gases, and soil vapor during an in-situ remediation effort. Results of periodic groundwater sampling events over a nine-month period showed a good comparison between the certified analytical lab and the field analysis, producing an r of .97 (slope of 1.06) (Aelion et al, 1996:232). Comparisons of VOC concentrations in SVE

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exhaust as measured in the field and in the lab produced an r of .95 (Aelion et al,
1996:233).

Kezners and Matz demonstrated a mean accuracy of 110 percent and 100 percent,
respectively, for two chlorinated ethenes in water at concentrations of 10 µg/L (Kesners
and Matz, 1993:2369). Hewitt and others compared field-based GC/photoionization
detector (PID) and laboratory-based GC/MS in the determination of four VOCs (trans-1,
2 dichloroethylene, 1,1,2 trichloroethylene (TCE), benzene, and toluene) in soil.
Comparisons of analytical results on two contaminant-fortified soils containing the four
VOCs determined mean values were not significantly different in 11 of 16 comparisons
(Hewitt et al, 1992:1934). The r for the regression between lab and field data was 0.98
(slope of 0.56).

NHSRC reported field-based GC performance evaluation sample results for 14
VOCs in water obtained during remedial investigation field work in EPA Region 9. Field
results ranged from 4.66 µg/L for TCE to 16.39 µg/L for carbon tetrachloride (NHSRC,
1998:A-47). The maximum deviation (in accuracy) from laboratory results was 4.1 µg/L
above the reported lab result for chloroform (NHSRC, 1998:A-47).

Soil samples fortified with high levels of VOCs (1-100 µg/g) analyzed via the
field-based GC/PID produced RSDs ranging from 1.0 percent to 11 percent, with a mean
of 5.0 percent (Hewitt et al, 1992:1934). Soil samples fortified with low levels of VOCs
(0.1-10 µg/g) analyzed via the field-based GC/PID produced RSDs ranging from 1.3
percent to 23 percent, with a mean of 7.9 percent (Hewitt et al, 1992:1934). Kesners and
Matz calculated RSDs of 9.0 percent and 5.0 percent for cis-dichloroethene and

tetrachloroethene standards in a water matrix spiked at 10 µg/l, respectively (Kesners and Matz, 1993:2369).

Comparisons of results from several field- and lab-based GC analytical experiments in varying matrix types containing chloroform, dibromochloromethane, bromoform, and bromodichloromethane produced RSDs ranging from 0.0 percent to 46 percent, while the mean RSD for all analyses was 19 percent (NHSRC, 1997:A-51).

Method Limitations. FRTR reports analyte detection limits for the field-based GC/MS system at 100-1000 ppb in soil and 1-50 ppb in water (FRTR, 1998). NHSRC reports that typical detection limits for analytes extracted into the gaseous phase will range from 5 to 200 ppb by volume (ppbv) (NHSRC, 1998:M1-87). Drugov reported detection limits of 0.05 mg/kg in the determination of 19 important PAHs in soils (Drugov, 1993:252). Berkley and others reported a limit of detection (LOD) range of 0.25 ppbv to 9.7 ppbv for a mixture of ten non-halogenated hydrocarbons and six chlorinated hydrocarbons in the gaseous phase (Berkley et al, 1992:133).

EPA-reported limitations include the following (EPA FASCT, 1997:12):

1. An experienced operator is required, otherwise a significant learning curve is associated with use and "trouble-shooting" of equipment;

2. The library of components (which the MS utilizes for contaminant identification) may be limited for the MS with some systems;

3. Contaminant carrier solvents must be carefully selected so as not to interfere with contaminant analysis;

4. Modification of normal extraction times may be required to improve consistency of results;

5. Diesel fuels showed poor extraction from soils with high organic content; and

6. Co-elution of multiple contaminant types hindered ability to meet detection limits.

FRTR notes that the selectivity of the process is highly dependent upon the detector type used, and contaminants contained in soil and water media require extraction to the gas phase (in the case of GC) prior to analysis (FRTR, 1998). Efficient extraction can present difficulties depending upon the matrix containing the contaminant(s). Kesners and Matz reported average extraction efficiencies ranging from 27 percent to 75 percent for 10 VOCs in water.

Hewitt and others note that field soils that are heterogeneous present difficulties in accurate analysis, owing to varying physical and chemical properties (e.g. organic content), varying contaminant-soil interaction properties, and variability of extraction efficiency (Hewitt et al, 1992:1936).

Anodic Stripping Voltammetry. Anodic stripping voltammetry (ASV) involves a two-step process consisting of electrolysis and stripping steps (NHSRC, 1998:M2-38). The electrolysis step involves a pre-concentration step during which metal ions of interest in solution are reduced to free metal and deposited on a working electrode. The electrolysis step is normally performed using a mercury or gold film-coated, glassy carbon electrode. The metal ions (positively charged) are deposited onto the working electrode by applying a negative voltage to the electrode, and this step usually takes between thirty seconds and two minutes (NHSRC, 1998:M2-38).

The measurements are recorded during the stripping step, during which metals are reoxidized and stripped back into solution in ionic form. The potential of the working

electrode is measured during stripping, and metals present in the sample are identified by their characteristic potential (NHSRC, 1998:M2-38). As long as a metal is being stripped off the working electrode, the potential remains stable. The stripping time for a metal is proportional to its concentration and serves as the basis for making a quantitative determination (NHSRC, 1998:M2-38). The concentration of several metals can be determined during a single measurement, since each metal is oxidized at a different potential.

Resource Requirements. NHSRC reports the cost of a standard sample analysis ranges from $15 to $20 per sample (NHSRC, 1998:M2-40). ASV field-portable meters can be purchased for approximately $4,000 to $5,000, while disposable calibration sensors cost approximately $300 to $400 per box of 20 sensors (NHSRC, 1998:M2-40).

Analyses can be completed in less than five minutes per sample (assuming sample extraction to aqueous phase has been performed), and thus it may be possible to analyze up to 50 samples per day (NHSRC, 1998:M2-42,M2-46). Alderman and others utilized a 15-minute electrolysis step time, and an overall sample analysis time of approximately 25 minutes per sample (Jones et al, 1998:26-27). Lu and others utilized field-based ASV to determine heavy metal concentrations (cadmium, zinc, copper and lead) in sediments at a Department of Energy (DoE) mixed waste landfill. They reported a 1 to 5 minute metal deposition time, and required approximately 10 minutes to complete a sample analysis (Lu et al, 1994:2077).

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Data Quality. Utilizing calibration chips or other calibration standards, as applicable to the equipment, this method provides quantitative data on analyte concentrations (NHSRC, 1998:M2-38).

In measuring copper II standard concentrations in six rice field waters and a catchment basin, Jones and others reported the mean reCVeries (accuracy of amount reCVered versus amount spiked) of 100+/-12 percent, with an r of .990 or better between ASV field analysis and laboratory analysis (Jones et al, 1998:29). Lu and others reported ASV results from nine analyses for copper (II) of 32.4 +/- 13.3 ppm, while laboratory results produced copper (II) concentrations of 33.1 +/- 11.3 ppm (Lu et al, 1994:2078).

Darling and others utilized in-situ ASV measurements to detect heavy metals in groundwater at a DoD National Priority List site in Massachusetts. They reported in-situ lead measurements of 302, 32 and 210 ppm, while confirmatory laboratory results were 898, 174, and 687 ppm, respectively (Darling et al, 1998:133).

NHSRC reported results of multiple analyses on several solutions spiked with lead at concentrations ranging from 116 to 898 $\mu g/L$. The average percent recovery was 99.9 percent with a standard deviation of 2.1 percent (NHSRC, 1998:M2-42). In another study, lead contamination analyses were performed in the field using ASV and in the laboratory using inductively coupled plasma spectroscopy. Regression analysis produced an r of 0.9885 (slope of 0.97, y-intercep of 0.07 $\mu g/L$) (NHSRC, 1998:M2-42).

NHSRC reports that the CV on samples analyzed via ASV has been shown to be ten percent of less on replicate analyses (NHSRC, 1998:M2-42). Darling and others

reported reproducibility among replicate samples of +/- 3 percent (Darling et al, 1998:133).

Method Limitations. NHSRC reports that detection limits for metals in water range from 1 to 100 ppb (NHSRC, 1998:M2-42). FRTR reports detection limit ranges of 100-1000 ppb in soil and 1 to 50 ppb in water (FRTR, 1998). Alderman and others, in their research into application to wastewater analysis, reported method detection limits for zinc, cadmium, lead, and copper to be 55, 71, 64, and 123 ppb, respectively (Alderman et al, 1998:412). Lu and others reported method detection limits for the four metals of 1.0 ppb (Lu et al, 1994:2077). Darling and others reported method detection limits for the four metals ranging from 4.0 ppb for copper (II) to 302 ppb for lead (Darling et al, 1998:133).

NHSRC reports the following limitations (NHSRC, 1998:M2-45):

1. Complexing agents can interfere with stripping measurements by forming a complex with the analyte such that the potential of the complex does not lie in the potential window of the analyte;

2. Surfactants can cause major errors in electroanalytical measurements since they adsorb on the electrode surface;

3. Metals with oxidation potentials close to that of the analytes may interfere if the instrument does not have sufficient resolution to resolve the overlapping peaks; and

4. Metals that form inter-metallic compounds/complexes with the analytes may result in erroneously low analyte concentration readings, since the oxidation potential of the compound/complex is rarely near that of the original analyte.

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Darling and others report that fouling of the electrode by natural organic matter may become a problem if the electrode is not properly treated by polymers, and that saturation of the electrode due to high concentrations of metal analytes may contribute to inaccurate data (although this can be overcome by modifying deposition times) (Darling et al, 1998:134).

ASV technology measures analyte concentration in the aqueous phase, and as such, metals not in solution (i.e. soil, air filters, etc.) require extraction into solution prior to quantification (FRTR, 1998).

Cone Penetrometer Mounted Sensor Systems. The cone penetrometer mounted sensor (CPMS) system usually consists of 1) an enclosed 20- to 40-ton truck equipped with vertical hydraulic rams that are used to force (or push, non-percussion) a sensor probe into the subsurface, 2) a data acquisition, processing, and data storage computer system, and 3) electronic signal processing equipment (FRTR, 1998). The cone penetrometer rod has a conical tip of up to two inches in diameter that is hydraulically pushed into the subsurface utilizing the weight of the truck to provide the force (maximum pressure of 80,000 pounds). As the rod progresses into the subsurface, a computer reads data from sensors located in both the tip and the side of the probe. In this manner, the cone penetrometer can monitor for contaminants, record soil properties, or collect confirmatory soil or water samples (FRTR, 1998).

Two of the major CPMS systems in-use include the Site Characterization and Analysis Penetrometer System (SCAPS) developed through a collaborative effort of the U.S. Army, Navy and Air Force under the Tri-Services Program, and the Rapid Optical Screening Tool (ROST™) developed by Fugro Geosciences (formerly Loral

Corporation) and Dakota Technologies, Incorporated (NHSRC, 1998:M1-35). Both systems utilized laser-induced fluorescence (LIF) for contaminant detection, identification, and "quatitation." The primary differences between the two systems are the laser and detector systems employed. The SCAPS-LIF system uses a pulsed-nitrogen laser, a photodiode array (PDA), and an optical multi-channel analyzer (OMA) as the fluorescence detector, with the PDA and OMA able to quantify the emissions spectrum from 350 nanometers (nm) to 720 nm (NHSRC, 1998:M1-37). The ROST™ system uses a tunable dye laser, a monochromator, a photomultiplier tube, and a digital storage oscilloscope, with the technician able to determine the wavelength of maximum intensity in the fluorescence spectrum or isolate the wavelength of a particular analyte, as desired (NHSRC, 1998:M1-37). For both LIF detection systems, the laser energy is deployed through a sapphire window, and the resulting fluorescent signal of the analyte is then captured through the same sapphire window.

The CPMS systems have standard sensors mounted to the rod which allow simultaneous monitoring of soil stratigraphy and petroleum hydrocarbon contamination data (NHSRC, 1998:M1-38). Other sensors capable of being mounted onto the rod assembly include video imaging, which provides insight into soil dynamics, allows grain size analysis, and may provide direct detection of contamination, and a soil moisture probe, which provides insight into vadose zone soil moisture properties (Huxley et al, 1998:G-10). The CPMS platforms also have survey and site mapping equipment, as well as equipment for decontaminating the penetrometer rods and backfilling each penetrometer push cavity (Huxley et al, 1998:G-10).

Resource Requirements. Costs reported by EPA for the CPMS system (SCAPS-LIF, ROST, and others) utilized for site characterization and remedial monitoring at 34 sites throughout the U.S. ranged from $2,300 per day to $4,600 per day at sites averaging a push rate of 200 feet per day (primarily the SCAPS-LIF), and up to $7,000 per day for sites with an average push rate of 290 feet per day (primarily ROST™) (EPA FASCT, 1997:22-29). Within the $2,300 to $4,600 per day cost range, the actual number of pushes ranged from a low of 8 (56 feet total) over 2 days to a high of 121 (1,667 feet total) over 21 days (EPA FASCT, 1997:22-29). FRTR reports an operational cost for the CPMS system of approximately $3,000 per day (FRTR, 1998). Bujewski and Rutherford reported costs ranging from $12 to $20 per foot with an average push rate of 200 feet per day (under normal conditions) for the SCAPS-LIF system (Bujewski and Rutherford SCAPS, 1996:3). They reported a daily rate for the ROST™ of $5,300 at an average push rate of 300 feet per day (under normal conditions) (Bujewski and Rutherford ROST, 1996:11-12).

The standard penetration rate for the systems is approximately two centimeters per second or four feet per minute (NHSRC, 1998:M1-38). Penetration rates can be as high as 180 +/- 30 feet per hour, but are typically 40 to 50 feet per hour (DOE, 1998). ASTM standards set two centimeters per second as a maximum push rate for data collection (DOE, 1998). Data collection is continuous (taking only seconds to collect, process and display) as the rod is advanced, except when confirmatory soil or water samples are to be collected.

NHSRC reports that both systems are capable of achieving 300 feet of pushes in a 10-hour workday (NHSRC, 1998:M1-46). During a SITE demonstration, three different

sites were characterized with the SCAPS-LIF and ROST™ systems, and the costs to produce contaminant cross-sections for the three sites were $42,000 and $41,000, respectively (as compared to $60,000 required to produce reference methods cross-sections using conventional drilling and formal laboratory methods) (NHSRC, 1998:M1-46).

Data Quality. NHSRC reports that the technology is intended to provide qualitative to semi-quantitative information about the distribution of subsurface petroleum contamination (NHSRC, 1998:M1-34). Through the use of prescribed standards and protocols prior to a push, semi-quantitative data can be obtained. Bujewski and Rutherford report that the SCAPS-LIF is primarily used as a field screening, qualitative method but can be semi-quantitative at concentrations within two orders of magnitude of its detection limit for fluorescent petroleum hydrocarbons (Bujewski and Rutherford SCAPS, 1996:1).

In a Consortium for Site Characterization Technology (CSCT) demonstration at two petroleum-contaminated sites (one tank farm and one fuel transfer facility), the SCAPS-LIF and ROST™ system were tested for site screening capability. Both systems produced results that were comparable to the confirmatory laboratory results, with better than 93 percent agreement between discrete soil sample analytical results (Bujewski and Rutherford SCAPS, 1996:2). The following were the results for the SCAPS-LIF: of 92 samples taken at the tank farm, results showed 0.0 percent false positives and 5.4 percent false negatives; of 130 samples taken at the fuel transfer facility, results showed 1.5 percent false positives and 3.8 percent false negatives (Bujewski and Rutherford SCAPS, 1996:58). The following were the results for the ROST™: of 92 samples taken at the tank

farm, results showed 3.3 percent false positives and 3.3 percent false negatives; of 130 samples taken at the fuel transfer facility, results showed 5.4 percent false positives and 5.4 percent false negatives (Bujewski and Rutherford ROST, 1996:39,44).

Technology field validation studies (site screening) at nine sites were conducted in the state of California for the SCAPS-LIF. Between 16 and 45 CPMS system pushes along with three to eight confirmation soil sample borings were completed at each site. For the 164 TPH analyses completed, results showed 5.5 percent false positives and 7.3 percent false negatives; for the 164 total recoverable petroleum hydrocarbon (TRPH) analyses, results showed 3.7 percent false positives and 9.8 percent false negatives (NHSRC, 1998:M1-47, M1-48).

Precision of the systems was determined during the CSCT demonstrations through the use of replicate measurements of standards. Using a 10 ppm standard solution and performing 20 replicate measurements provided an RSD of less than 1.0 percent for the SCAPS-LIF system (Bujewski and Rutherford SCAPS, 1996:58). Using a reference standard and performing 20 replicate measurements provided an RSD of 2.2 percent for the ROST™ system (Bujewski and Rutherford ROST, 1996:37).

Method Limitations. Site-specific detection limits are difficult to determine and will vary between sites and petroleum products, but generally range from 50 to 1,000 mg/kg (NHSRC, 1998:M1-46). Aldstadt and Martin reported that detection limits of target analytes employing LIF are in the vicinity of 100 ppm (Aldstadt and Martin, 1997:8). Based upon results of various SCAPS-LIF deployments, Bujewski and Rutherford reported that the detection threshold will vary somewhat from site to site and day to day, but is approximately 100 to 300 mg/kg TRPH (Bujewski and Rutherford

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SCAPS, 1996:11). In addition, nonlinearity tends to occur at concentrations greater than 10,000 mg/kg, signaling a potential upper limit of reliable "quantitation" (Bujewski and Rutherford SCAPS, 1996:11).

The SCAPS-LIF detection limits reported in the CSCT demonstration were 105 mg/kg at the fuel transfer facility and 89 mg/kg at the tank farm (Bujewski and Rutherford SCAPS, 1996:39,45). The ROST™ detection limit reported at the tank farm was 41 mg/kg and was 5 mg/kg at the fuel transfer facility (Bujewski and Rutherford ROST, 1996:39,43).

The CPMS systems are designed for use on level to gently sloping terrain with clayey to sandy soils having small gravel sizes (Ames Lab, 1998). The air space above the truck must be free of obstructions (e.g. power lines) and the subsurface in the immediate vicinity of the CPMS push must be free of buried objects (e.g. utilities). The CPMS rod will not penetrate boulders, cobbles, rubble, well-compacted sediment, or sound bedrock (Ames Lab, 1998). The unit can be operated in all weather, although weather extremes will impact operations. In particular, cold weather may cause problems with freezing of the grout and steam cleaning water lines and hot weather may cause discomfort to operating personnel, especially when personal protective equipment must be worn (Ames Lab 1998).

All sources acknowledge that the operation of the CPMS system takes considerable experience. Some maintenance of the CPMS system tools and the LIF sensor is required, and breakdowns can be expected on long-term projects (NHSRC, 1998:M1-46). Downtime due to breakage of fiber-optic cables, breakage of push rods,

fogging of the sapphire window, and problems with the grout pump or decontamination unit may occur (NHSRC, 1998:M1-46).

Other reported limitations include the finding that LIF sensors are limited to a depth of approximately 50 meters due to attenuation in optical fiber umbilical cord and that minerals such as calcite and naturally-occurring organic matter also can flouresce, which may cause interference problems (NHSRC, 1998:M1-46). Bujewski and Rutherford point out that the LIF sensor is sensitive to variations in the soil matrix, such as soil grain size, mineralogy, moisture content, and surface area, as these variations influence the relative amount of analyte adsorbed onto or absorbed into the soil, in turn affecting how much is optically accessible to the window (Bujewski and Rutherford SCAPS, 1996:12).

Aldstadt reports that a key limitation of LIF techniques is that the silica optical fibers can be used only with visible sources (wavelength > 260 nm), thus precluding their use in the ultraviolet (UV) region and limiting their ability to analyze samples containing compounds with single aromatic rings (e.g. BTEX compounds) (Aldstadt and Martin, 1997:9). In addition, a major group of contaminants, the chlorinated aliphatic hydrocarbons (e.g. TCE), cannot be measured using LIF (Aldstadt and Martin, 1997:9).

Biosensors. A biosensor is an analytical device composed of a biological recognition element directly interfaced with a signal transducer which together relate the concentration of an analyte (or group of analytes) to a measurable response (Mascini and Rodgers, 1998). Biosensors for environmental applications have employed a wide range of biological recognition systems coupled to a similarly wide range of signal transducers. Biological recognition is accomplished via three primary mechanisms, including

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biocatalytic-, bioaffinity-, and microbe-based systems (Mascini and Rodgers, 1998). These biological recognition systems have been linked to electrochemical, optic-electronic, optical, and acoustic transducers in order to identify and quantify analytes of interest (Mascini and Rodgers, 1998).

Biocatalytic-based systems employ enzymes that aid in either the catalytic transformation of the pollutant into a sensor-detectable form or inhibition of the enzyme activity by the pollutant (Mascini and Rodgers, 1998). Bioaffinity-based systems utilize antibodies to selectively bind the analyte or nucleic acids that identify the analyte through pollutant-induced DNA damage or hybridization to a species-specific sequence (Mascini and Rodgers, 1998). Microorganism-based systems utilize several mechanisms in analyte detection and quantification, including pollutant-dependent increase in cellular respiration, inhibition of cellular respiration by the pollutant, and promoter organism recognition of a specific pollutant followed by gene expression, enzyme synthesis, and catalytic activity (Mascini and Rodgers, 1998).

Biosensors are relatively small, and they can be used separately or as modular detectors in larger systems. In addition, many types, such as the bioaffinity-based systems, are multi-use and can be recharged or regenerated.

Resource Requirements. Gerlach and Rogers report that in a field demonstration utilizing biosensors for explosives detection, the cost per sample was $8, however expenses for start-up costs were $20,000 (Gerlach and Rodgers, 1996). Donner and others employed a portable fiber-optic biosensor for on-site analysis of trinitrotoluene (TNT) and other explosives and degradation products. They estimated the cost of the fiber-optic biosensor at $3 per sample (Donner et al, 1997:841). Bart and

others utilized biosensors to detect explosives in detonation area runoff lagoon sediments. They reported a projected cost of less than $10 per sample (Bart et al, 1997:1510).

Donner and others reported it takes approximately 16 minutes to run the sample and a 100 percent reference solution in quadruplicate or to run four separate samples individually on the fiber-optic biosensor (Donner et al, 1997: 841). EPA reported throughputs of 10 to 30 samples per day for military explosives detection (TNT, RDX, HMX) in soil and groundwater (EPA FASCT, 1997:21). Cai and others utilized a DNA biosensor system to detect hydrazines in groundwater. They reported reaction times of one to ten minutes, depending upon the target analyte concentration, for monitoring ppb levels of different hydrazines (Cai et al, 1996:2252). Cammann and others utilized the optoelectronic biosensor, based on surface plasmon resonance, in order to detect pesticides in aqueous solution. They reported a one-hour reaction time for ppb levels of pesticides in solution (Cammann et al, 1998:456). Campanella and others utilized immobilized toxicity cell biosensors based on cell respiratory perturbation and incorporating various electrodes (oxygen, carbon dioxide, glass, and solid state). They reported an analytical time of 15 minutes (Campanella et al, 1997:282). Bart and others reported that they were able to analyze both a sample and a standard in less than ten minutes (Bart et al, 1997:1510).

Data Quality. Biosensors for environmental applications cover a broad range of compounds across a number of chemical classes. The various recognition element and transducer combinations provide semi-quantitative to quantitative data, depending upon the use of standards and protocols, and whether the sample will be analyzed in-situ or ex-situ.

Donner and others compared quantified results for TNT, trinitrobenzene sulfonic acid (TNB), and other explosive degradation products. They reported that analytical comparisons between the fiber-optic biosensor and confirmatory laboratory results produced an r of .96 (slope of 1.18, y-intercept of 17.5 µg/L) (Donner et al, 1997:840). In addition, results for just TNT and TNB produced an r of .98 (slope of 1.09, y-intercept of 5.22 µg/L) (Donner et al, 1997:840). Bart and others also compared biosensor and lab results for detection of explosives in sediment samples. They reported an r of .91 (slope of 1.05, y-intercept of 277 ppb) for TNT and TNB (in ppb) comparison results, and an r of .94 (slope of 0.82, y-intercept of 25 ppb) for RDX and HMX (in ppb) comparison results (Bart et al, 1997:1507-1508).

The immobilized toxicity cell biosensors used by Campanella showed a RSD range of 4.7 percent to 6.6 percent for cadmium detection, and a RSD range of 3.8 percent to 8.9 percent for mercury (II) (Campanella et al, 1997:283). Baer and others determined the CV in bioluminescence (which they used to identify and indirectly quantify VOC toxicity) ranged from 1 percent to 3 percent on untreated replicate water samples and from 4 percent to 25 percent on untreated replicate soil samples (Baer et al, 1998:1042-1043). Cai and others proposed the interaction of various hydrazines with the DNA surface layer results in a reproducible response. Prepared samples contained 1.5 µg/L methylhydrazine, 3 µg/L dimethylhydrazine, and 30 µg/L diphenylhydrazine. In performing the tests to detect the particular analytes, six replicates were run on each of three tests, and they reported RSDs of 3.9 percent, 5.4 percent, and 5.7 percent, respectively (Cai et al, 1997:2253).

Method Limitations. The detection limits for bisensors vary according to the type/class of analyte, the analyte matrix, and selection of the appropriate biological sensing element and transducer combination, among others. By optimizing the biological assay with the most appropriate transducer, it is possible to detect extremely low concentrations of a wide array of compounds of environmental concern (Gerlach and Rodgers, 1996).

Campanella and others reported a detection limit of cadmium in industrial wastewater of 0.01 millimoles (mmol)/L (~ 1.0 ppb) and a detection limit of mercury (II) ranged from 0.01 to 0.05 mmol/L (~ 2.0 to 10 ppb) (Campanella et al, 1997:283). Mascini and Rogers reported a detection limit of 10 nanomoles (nM) for mercury (II) and detection limits for other environmentally significant metals in the low nM range (Mascini and Rodgers, 1998). They also reported detection limits for cholinesterase biosensors are in the $\mu g/L$ to ng/L range for compounds such as aldicarb, carbaryl, and carbofuran. Donner and others reported a detection limit for TNT and other explosives in groundwater of 20 $\mu g/L$ (Donner et al, 1997:841). Bart and others reported a detection limit of 50 ppb for the various explosives (Bart et al, 1997:1507). Cai and others reported detection limits of 0.5 $\mu g/L$ for methyl and dimethylhydrazines, 10 and 15 $\mu g/L$, respectively, for phenyl and diphenylhydrazines, and 2 mg/l for total hydrazine (Cai et al, 1996:2253). Caamann and others reported detection limits of 0.05 to 5.0 $\mu g/L$ for various photosynthesis-inhibiting pesticides in aqueous solution (Caamann et al, 1998:456).

Conceptually, one of the primary limitations to the use of biosensors is that the user is dealing with a biological system as the sensing element, and oftentimes, biological systems can react with surprising results. Biocatalysis-based biosensors have limitations

imposed by the nature of the enzyme itself and include the limited number of environmental pollutants which happen to be a substrate for the enzyme (Mascini and Rodgers, 1998). This method is subject to interference and co-contamination of samples that may lead to unexpected results (e.g. co-contamination of samples with organics and heavy metals) and little work has focused on the development of membrane barriers for the direct sampling of groundwater or pore water in sludges and saturated sediments (Mascini and Rodgers, 1998).

Microorganism-based system limitations include variability encountered in calibration of the biosensor response to analytes and the presence of polymers and other substrates (Mascini and Rodgers, 1998). Additional limitations include relatively long assay times and the broad specificity of some biosensors to environmental toxins (Mascini and Rodgers, 1998).

Other general limitations for the method include the following (Mascini and Rodgers, 1998): a limited number of genetically-engineered microorganisms constructed to respond to specific environmental pollutants exist; extraction of the analyte from soil or sediment matrices is normally required, and the potential necessity for filtration and concentration steps for all matrices also may be required; the transducer should be calibrated in the relevant sample matrix; many methods cannot distinguish between specific compounds, only providing total concentrations for classes of compounds; for some methods, as analyte concentrations reach saturation, small changes in inhibition results in large changes in reported concentrations, significantly decreasing accuracy (i.e. the user needs to know the linear range of the specific technique being used).

Graphite Furnace Atomic Absorption Spectroscopy. Atomic absorption spectroscopy uses the absorption of light to measure the concentration of gas-phase atoms. Ground-state atoms absorb energy in the form of ultraviolet (UV) or visible light and are elevated to an excited state. The amount of light energy absorbed increases as the concentration of the selected element increases (NHSRC, 1998:M2-50).

Since samples are usually liquids or solids, the analyte must be vaporized in a flame or graphite furnace (in current field technology, the graphite furnace is used). Ions or atoms in a sample must undergo desolvation and vaporization in the graphite furnace (Science Hypermedia, 1999). The graphite furnace atomic absorption spectrometer (GFAAS) is an efficient atomizer that can accept solutions, slurries, or solid samples (although the field GFAAS has primarily been used for slurries and solutions). Samples are placed directly in the graphite furnace and the furnace is electrically heated in several steps to dry the sample, ash the organic matter, and vaporize the analyte atoms (Science Hypermedia, 1999). Monochromators filter background light due to interferences and isolate the wavelength of interest, and a detector records UV and visible light intensity changes in order to identify and quantify analytes (Science Hypermedia, 1999).

Analytical methods based on atomic absorption are potentially highly specific, because atomic absorption lines are remarkably narrow (0.002 to 0.005 nm) and electronic transition energies are unique for each element (Leary and Skoog, 1992:212).

Resource Requirements. Wach reported on sample analysis costs for various manufacturers of GFAAS technologies. Costs ranged from $32 per sample to $75 per sample depending upon the number, types, and variety of samples (Wach, 1995:52A-53A).

NHSRC reports that samples are commonly analyzed in triplicate, but the analysis procedure only requires approximately five minutes (NHSRC, 1998:M2-50). Hernandez-Cordoba and others utilized GFAAS to determine arsenic and antimony contamination in soils and sediments. They utilized a 15-minute extraction step followed by analysis (Hernandez-Cordoba et al, 1997:439).

Data Quality. GFAAS provides quantitative data, using calibration standards and periodic performance standards, for inorganic analyses (primarily heavy metals).

Hernandez-Cordoba and others compared GFAAS and laboratory analyses, and reported r greater than 0.95 for arsenic in two soils and three sediments, and r greater than 0.93 for antimony in two soils and three sediments (Hernandez-Cordoba et al, 1997:440). Caricchia and others utilized GFAAS in the determination of organotin compounds in sea water and sediments. Correlation (r) between GFAAS and laboratory data for four forms of tin ranged from 0.997 and 0.998 (Caricchia et al, 1993:51). Andonie and others analyzed atmospheric rainwater in order to determine metal content. Regression analysis comparing field to lab data produced r of 0.97, 0.98, and 0.99 for copper, cadmium and lead, respectively (Andonie et al, 1993:132). NHSRC reported that protocol for GFASS includes analysis of a method blank with each batch of ten samples, and no blank should register any analyte above the practical quantitation limit (improving accuracy) (NHSRC, 1998:M2-52).

Hernandez-Cordoba and others reported that for each arsenic sample suspension, five replicates were analyzed, and the RSDs ranged from 3.0 to 5.5 percent; for antimony, the RSD for 10 replicates of a single prepared suspension (20 mg/l) was 1.9 percent,

while that for 25 measurements obtained by preparing five suspensions from the same sample and analyzing five aliquots each was 2.4 percent (Hernandez-Cordoba et al, 1997:443). Caricchia and others reported a precision of greater than 90 percent for organotin compounds in water samples, and approximately 85 percent for organotins in sediments (Caricchia et al, 1997:37). Andonie and others reported that the CV for lead quantitation ranged from a low of 7 percent for cadmium to a high of 23 percent (Andonie et al, 1993:132). Freedman and others measured copper and cadmium in aquifer colloids. They reported RSDs ranging from 5 percent to 31 percent for copper and from 4 percent to 27 percent for cadmium (Freedman et al, 1996:2275).

Method Limitations. FRTR reports MDLs of 100 to 1000 ppb for analytes in a soil matrix and MDLs of 1 to 50 ppb for analytes in an aqueous matrix (FRTR, 1998). Mach and others conducted a study of metals emanating from steam-electric power plant discharges. With their instrument, they reported MDLs of 0.5, 0.6, 0.1/0.1, and 0.7 μg/l for arsenic, selenium, chromium (III and VI), and lead (Mach et al, 1996:277). Hernandez-Cordoba and others reported detection limits for arsenic in soil of 1 μg/g and detection limits of 0.03 μg/g for antimony in soil (Hernandez-Cordoba et al, 1997:441, 443). NHSRC reports detection limits of 0.5 to 10.0 μg/l for metals in an aqueous matrix (NHSRC, 1998:M2-50). Caricchia and others reported detection limits for tin, given the various organotin compounds they analyzed, of 0.2 ppb (Caricchia et al, 1993:49).

Limitations reported by NHSRC include the need for a 220-volt power source and logistic concerns such as having sufficient reagents for sample preparation and analysis and ensuring an adequate supply of matrix modifiers (NHSRC, 1998:M2-50). In

addition, they report that contamination of the sample, which can easily occur, may become a major source of error due to the extreme sensitivities achieved with the furnace. NHSRC reports that GFAAS requires a longer analysis time than flame sampling, the method is not a multi-element analysis (furnace temperature protocol, monochromator selection, and detector set to determine single element per analysis), the dynamic range of concentration detection is limited, and the method is susceptible to high matrix interferences (NHSRC, 1998:M2-54)

The requirement (at least at the current time for the field GFAAS) for extraction of the analyte from a solid matrix can greatly affect the accuracy of reported analyte concentrations. Hernandez-Cordoba and others reported extraction efficiencies ranging from 35 percent to 92 percent for arsenic and efficiencies ranging from 35 percent to 45 percent for antimony extracted into slurries (Hernandez-Cordoba et al, 1997:440-441). Caricchia and others reported extraction efficiencies for various organic forms of tin ranging from 81 percent to 94 percent (Caricchia et al, 1993:46). In addition, they noted that determination of organic forms of tin and other metals in real matrices is often hindered by interferences from other matrix components during ashing and atomization.

Flame Ionization Detector. Portable flame ionization detector (FID) instruments detect organic compounds by first using a sampling pump to feed the analyte/air mixture into a mixing chamber. The mixture is then ignited as it passes over a pure hydrogen flame, which breaks down the organic molecules and produces ions. The ions gather on a collection plate where a current is generated as a result of the high voltage applied across the detector and the organic ions and electrons present in the gas

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(FRTR, 1998). The magnitude of the current is proportional to the concentration of organic vapors within the gas (FRTR, 1998).

FIDs are commonly used as detectors following non-destructive analyte separation technologies, such as GC. This allows for an accurate quantitative analysis. However, the FID used alone can still provide important information on site contamination. FIDs have some advantages over other instruments in that they have a wider measuring range (dynamic range) and response to hydrocarbons (including methane) and they do not give false positive readings when water vapor is included with the sample (FRTR, 1998).

Resource Requirements. NHSRC reports that typical rental costs for hand-held FID instruments range from $200 to $300 per week or $800 to $1,000 per month, while typical purchase prices range from $7,000 to $10,000, depending upon manufacturer (NHSRC, 1998:M1-5). Hermon-Cruz, who studied portable reading instruments, reported costs for FID purchase ranging from $4,000 to $7,000, again depending upon type and manufacturer (Hermon-Cruz, 1998:6). EPA Office of Underground Storage Tanks (OUST) reported costs ranging from less than $1 to approximately $10 per sample (EPA OUST, 1999).

Dropkin and Sigsby compared hydrocarbon analysis via FID with that of a detailed GC analysis. They reported an analysis response time of 7 to 10 seconds for various grades of fuel and a maximum of 22 seconds for the larger, straight-chain hydrocarbons (e.g. n-dodecane) (Dropkin and Sigsby, 1990:820). Evans and Liikala, who analyzed hydrocarbon contamination in the soil resulting from a fuel spill, reported in-situ sample gas collection times of five minutes prior to performing the analysis

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(Evans and Liikala, 1997:345). EPA OUST reported sample collection and analysis times ranging from 1 to 30 minutes (EPA OUST, 1999).

Data Quality. Data quality is considered screening level because the results are non-compound specific (NHSRC, 1998:M1-9). The data produced by the portable FID is semi-quantitative due to the fact that the concentration of total VOCs is reported, but the specific compounds present are not identified (NHSRC, 1998:M1-9).

Begerow and others compared FID analysis against confirmatory laboratory analysis in determining hydrocarbon concentrations in soil gas samples. They reported accuracies of 61 percent to 68 percent for the various samples tested (Begerow et al, 1995:552). FID accuracy in a methodology utilizing jar headspace screening analysis ranged from 55 percent to 65 percent of laboratory-measured sample concentration (Fitzgerald, 1992:59). Fitzgerald reported benzene soil headspace concentration accuracy ranged from 50 percent to 90 percent of laboratory results (Fitzgerald, 1992:63).

Bristol and others used portable PID, FID and GC to test a field screening method for gasoline contamination. Correlation between the field and laboratory data for spiked soil headspace concentrations was 0.957 and 0.989 for benzene and gasoline, respectively (Bristol et al, 1989:92).

Dropkin and Sigsby reported an RSD of 15 percent for FID analysis of replicate samples of 11 hydrocarbons (Dropkin and Sigsby, 1990:819). Hermon-Cruz reported precision estimates of +/- 20 percent for several instruments and +/- 1 ppm for other instruments (Hermon-Cruz, 1991:8). Begerow and others reported RSDs ranging from 9.3 percent to 18.4 percent for various hydrocarbons in the sample (Begerow et al,

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1995:552). Fitzgerald reported that the RSDs of soil headspace and aqueous headspace analysis ranged from 5 percent to 15 percent (Fitzgerald, 1992:59).

Method Limitations. NHSRC reports detection limits in the low ppm range (approximately 0.2 ppm) for VOCs, with a dynamic range of approximately 0 to 50,000 ppm (NHSRC, 1998:M1-10). FRTR reports detection limits of 100 to 1,000 ppb for analytes in a soil matrix and 1 to 50 ppb for analytes in an aqueous matrix (FRTR, 1998). Hermon-Cruz reported detection limit ranges of 0.1 to 1.0 ppm for various FID instruments (Hermon-Cruz, 1991:8). Begerow and others reported detection limits ranging from .61 μg/cubic meter (approximately ppb) to 1.51 μg/cubic meter for the aromatic hydrocarbons in their study (Begerow et al, 1995:552). Bristol and others reported the limits of detection for benzene and BTEX from aqueous samples were approximately 30 μg/L and 20 μg/L, respectively (Bristol et al, 1989:91).

The FID is extremely efficient for providing a quick assessment of the total VOC concentrations in the matrix being analyzed, however, the instrument is primarily utilized to identify non-halogenated aromatic and straight-chain petroleum hydrocarbons (e.g. BTEX, gasoline components, diesel components), some low molecular weight halogenated compounds (e.g. carbon tetrachloride, methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK)), and other gases with an appreciable ionization potential (e.g. hydrogen cyanide) (NHSRC, 1998:M1-6). The FID will generally not detect halogenated VOCs unless the concentration is quite high (NHSRC, 1998:M1-7). In addition, the detector is destructive of the sample and hydrogen gas, which is flammable, must be supplied.

Depending upon DQOs and desired accuracy, some VOCs may require a separate extraction step prior to analysis (instead of drawing from the sample headspace). Generally, accurate readings can only be determined for the calibration gas and other analyte concentrations can be roughly determined using manufacturer-supplied conversion charts (FRTR, 1998). High humidity can cause the FID to flame out or not ignite at all, which can be significant when soil moisture levels are high or when an in-situ soil gas sampling point penetrates groundwater (FRTR, 1998). In addition, rapid variations in temperature at the detector and strong electrical fields may affect instrument response.

Dropkin and Sigsby reported that FID analysis for total hydrocarbon content was found to yield results 23 percent lower than that of the detailed GC analysis (Dropkin and Sigsby, 1990:818). Hermon-Cruz reported the FID detector has a linear response over a large range, but changes in geometry, flow and composition of the sample being supplied to the flame can alter the response of the detector (Hermon-Cruz, 1991:6).

The FID saturates when the hydrocarbon concentration entering the flame is large enough to lower the flame temperature, thereby decreasing the ionization efficiency (Gaffney and Marley, 1998:1440). This upper limit of the dynamic range can only be extended at the sacrifice of the lower limit of the dynamic range (i.e. higher detection limits).

Fiber Optic Chemical Sensors. Optical fibers are fine strands of glass, fused silica, or plastic that are capable of transmitting radiation over distance (Leary and Skoog, 1992:108). By suitable choice of construction materials, fibers that will transmit UV, visible, or IR can be manufactured.

Fiber optic sensors (also called optrodes) consist of a reagent phase immobilized on the end of a fiber optic. Interaction of the analyte with the reagent creates a change in absorbance, reflectance, fluorescence, or luminescence, which is then transmitted to a detector via the optical fiber (Leary and Skoog, 1992:109). Fiber optic sensors are generally simple, inexpensive (as compared to lab-based equipment) devices that are readily miniaturized for field applications (Leary and Skoog, 1992:109).

Fiber optic responses are transmitted to the various detectors, which include the spectroscope, colorimeter, photometer, fluorometer, spectrophotometer, and spectrofluorometer. A spectroscope is an optical instrument used for visual identification of emission lines, while a colorimeter is an instrument for absorption measurements in which the human eye serves as the detector (Leary and Skoog, 1992:110). A photometer consist of a source, filter, photoelectric detector plus a signal processor and readout, while photometers designed specifically for fluorescent measurements are fluorometers (Leary and Skoog, 1992:110). Monochromators with a fixed slit in the focal plane are called spectrometers, while a spectrometer equipped with a photoelectric detector is a spectrophotometer (Leary and Skoog, 1992:110). A spectrophotometer for fluorescence analysis is called a spectrofluorometer. Spectrophotometers are employed for absorbance measurements in the UV, visible, and IR regions and for fluorescence measurements in the former two (Leary and Skoog, 1992:110).

Resource Requirements. Barber and others utilized an UV absorption sensor to monitor the composition of vapor extractant from soil remediation wells. They reported a total cost per sample of $30, which included initial instrument assembly, installation, site staffing, and data analysis (Barber et al, 1995:1579-1580).

EPA OUST reports a cost per sample ranging from less than $1 per sample to $10 per sample (EPA OUST, 1999).

EPA reported data on the use of various fiber optic chemical sensors at three sites utilized in the detection of VOCs, SVOCs, BTEX, and TPH. They reported a range for sample analysis from continuous measurements (in-situ) to 10 minutes per sample (ex-situ analysis) (EPA FASCT, 1997:29). Anheier and others utilized a fiber-optic spectrochemical emissions sensor to detect halogentaed VOCs pulled into the air phase. They reported a sample collection and analysis time of 3 to 4 minutes and an additional 4 to 5 minutes to purge the system and return to baseline (Anheier et al, 1993:452). Blair and others analyzed aqueous samples of VOCs using an evanescent fiber optic chemical sensor. They reported that with their instrument, a 20 minute analysis time was sufficient (Blair et al, 1997:2241). Kellner and others used a near-IR fiber optic chemical sensor for in-situ measurements of chlorinated hydrocarbons in groundwater. They reported quantification could be performed within 10 minutes, giving linear calibration graphs for each species (Kellner et al, 1993:1486). EPA OUST reports an analysis time per sample ranging from 3 to 5 minutes (EPA OUST, 1999). Robbins tested a fiber-optic chemical sensor that can be used to screen soil gas, water, or soil for hydrocarbon contamination. He reported that the sensor required approximately 25 minutes to calibrate and was at 95 percent response (to the analyte) after five minutes (Robbins, 1996:3-19).

Data Quality. Fiber optic chemical sensors provide quantitative data when standards and DQO protocols are utilized in conjunction with field analysis. Barber and others reported a correlation between field data and laboratory data (GC/FID and GC/MS) of .994 (Barber et al, 1995:1578). Blair and others reported correlation of

0.97 and 0.98 for TCE and TCA, respectively and a correlation of 0.70 for toluene (Blair et al, 1997:2245). Kellner and others utilized an IR fiber-optic chemical sensor for in-situ measurements of chlorinated hydrocarbons in groundwater. They reported a correlation of .968 for perchloroethylene (PCE) in groundwater in the concentration range of 1 to 10 ppm (Kellner et al, 1993:1486). In comparing field and laboratory data, Robbins reported relative accuracy ranging from 8.2 percent for total BTEX to 12.3 percent for toluene (Robbins, 1996:3-22).

Bando and Blair reported instrument precisions of +/- 6, 9, 6 and 16 ppm for analysis of samples containing TCE, TCA, toluene and chloroform in the concentration range of 50 to 200 ppm (Bando and Blair, 1998:297). Blair and others reported the precision of their instrument, determined from 27 replicate samples, was +/- 26, 29, and 22 ppm for TCE, TCA and toluene, respectively (Blair et al, 1997:2243). Kellner and others reported an RSD of 17 percent for TCE concentrations (Kellner et al, 1993:1487). Robbins reported RSDs ranging from 2.0 percent for ethylbenzene to 4.6 percent for benzene (Robbins, 1996:3-22).

Method Limitations. Buckman reports that detection limits for most organic contaminants having absorption data available are in the parts per trillion (ppt) to ppb range (Buckman, 1993:517). Barber and others reported a detection limit of 13 ppmv for benzene in effluent air. Anheier and others reported a detection limit of 1 ppm for TCE extracted into the gaseous phase (Anheier et al, 1993:452). Kellner and others reported method detection limits for six chlorinated VOCs in groundwater ranged from 1 ppm for PCE to 50 ppm for 1,2,4-trichlorobenzene (Kellner et al, 1993:1486).

Robbins reported that for vapor measurement or headspace measurement for soil screening, the probe should be zeroed in an environment where the relative humidity closely matches that of the sample (Robbins, 1996:3-19). He noted, depending upon the reagent phase on the probe, decontamination after sampling can require numerous steps and several decontaminating agents. He reported sensor response was different for different types and conditions of gasolines, with these responses attributable to differences in aromatic content (Robbins, 1996:3-20). Thus, variations in the relative abundance of aromatics can affect the correlation of instrument reading with contaminant concentration. He found the instrument to have a higher sensitivity in detecting diesel than gasoline, favoring detection of the heavier aromatics (PAHs). Other environmental factors that can influence instrument response include humidity, direct sunlight, and extremes in temperature (Robbins, 1996:3-23).

The EPA reported that in their studies, the concentrations of analytes affects response time and possible interference may occur in measuring halogenated VOCs due to the presence of compounds similar in molecular structure and the presence of degradation daughter products (EPA FASCT, 1997:29). They reported that for ex-situ analysis, results are greatly affected by sample collection method (e.g. bailing or pumping) and the volume of the sample collected and tested.

Other limitations of this technology include limitations inherent with the sensing technology utilized, whether UV, visible or IR. Matrix interferences, required sample preparation steps, and response of analytes within often complex mixtures must be considered prior to technology application.

Photoionization Detector. The photoionization detector (PID) is a device that uses UV light as a means of ionizing an analyte in order to determine its concentration. Air (from headspace or a grab sample, which contains the analyte(s)) is continuously drawn through the instrument with an internal pump or fan. The air is exposed to an UV light source that emits photons with a specific energy. Available UV light source energies range from 8.4 electron-volts (eV) to 11.7 eV (Robbins, 1996:3-4). The photons can ionize organic molecules having an ionization potential (which is the energy needed to remove the outermost electron of the molecule) less than the UV source energy. The ions and free electrons are attracted to electrodes held at an applied voltage which produces an electric current. The electric current is measured and an output electric signal is developed that is proportional to the concentration of ionized molecules (Robbins, 1996:3-4). Each compound has a unique ionization potential that results in different ionization efficiencies (i.e. different degrees of response or detectability for different compounds), leading to analyte identification and analyte group quantitation.

Resource Requirements. EPA OUST reports a cost of $1 to $10 per sample utilizing the PID (EPA OUST, 1999). FRTR reports instrument rental costs of $150 to $300 per week with an estimated purchase price of $4,000 to $6,000 (FRTR, 1998). NHSRC reports typical rental costs of $150 to $300 per week or $500 to $1,000 per month, with purchase costs ranging from $4,000 to $6,000 (NHSRC, 1998:M1-5). Robbins reported that PID costs typically range from $3,000 to $6,000, with replacement lamps costing from $200 to $800 (Robbins, 1996:3-7). Hermon-Cruz reported that PID prices are between $4,000 and $7,000 and can run up to $25,000 or more with an optional GC unit (Hermon-Cruz, 1991:4).

EPA OUST reports sample collection and analysis time of 1 to 30 minutes (EPA OUST, 1999). Bristol and others reported that in performing aqueous headspace analyses, agitation times from 0.5 to 8.0 minutes were utilized, with steady-state conditions achieved in approximately 4.0 minutes (Bristol et al, 1989:89-90). For soil headspace analyses, equilibrium occurred within 30 seconds (Bristol et al, 1989:93).

FRTR reports a turnaround time of minutes per sample (FRTR, 1998). Chriswell and others utilized electrolytically-generated hydrogen as a purge gas to isolate VOCs in groundwater prior to PID analyses. They reported a 10 to 20 minute sample purge time prior to analysis (Chriswell et al, 1993:2380). Deyo and others utilized a variable-flow pump to collect soil-gas samples to determine gasoline contamination. They required approximately 3 to 12 minutes to collect samples and an additional 2 to 5 minutes for analysis (Deyo et al, 1990:111).

Data Quality. Data quality is considered screening level because the results are non-compound specific (NHSRC, 1998:M1-9). The data produced by the portable PID is semi-quantitative due to the fact that the concentration of total VOCs is reported, but the specific compounds present are not identified (NHSRC, 1998:M1-9).

Fitzgerald reported that in using the PID for headspace analyses, meter response indicated analyte concentrations that were approximately 50 percent of spiked aqueous and soil concentrations (Fitzgerald, 1992:59). Bristol and others reported a PID correlation coefficient of 0.998 for measured headspace concentration versus aqueous xylene concentration (Bristol et al, 1989:92). Deyo and others reported an r of 0.783 for PID-measured analyte concentrations versus laboratory-measured concentrations (Deyo et al, 1990:116). Robbins reported on a study in which several PID instruments (and

various other portable instruments) were used to analyze soils spiked with "fresh" gasoline and gasoline-contaminated soils from UST sites. He determined that the headspace readings for the different instruments exhibited poor correlation both with each other and with the laboratory results (Robbins, 1996:3-11).

Fitzgerald reported RSDs ranging from 5 percent to 9 percent for replicate headspace analyses using the PID (Fitzgerald, 1992:59). Hermon-Cruz reported that the precision of several instruments she researched was +/- 0.1 ppm and for others was +/- 1 percent (Hermon-Cruz, 1991:7). Bristol and others reported that reproducibility (precision) for aqueous soil headspace analyses using the PID ranged from 10 percent to 15 percent (Bristol et al, 1989:93). Robbins reported that in a study performed at a petroleum-contaminated soil site, the PID exhibited RSDs ranging from 10 percent to 15 percent, and in another study exhibited an RSD of 17 percent (Robbins, 1996:3-14). He reported that the precision for aqueous samples depended upon the analyte concentration(s), with an RSD of less that 5 percent at 500 ppb total BTEX, and up to an RSD of 49 percent at 10 ppb total BTEX (Robbins, 1996:3-14).

Method Limitations. FRTR reported detection limits of 10 ppm to 100 ppm for analytes in a soil matrix and 0.5 ppm to 10 ppm for analytes in the aqueous phase (FRTR, 1998). Robbins reported that the detection limits for the PID are in the fraction of ppm range, and the linear range for gasoline vapors is between 100 ppm and 1,000 ppm, depending upon the instrument (Robbins, 1996:3-6). Robbins cited a study by Photovac and reported detection limits of 0.5 mg/kg and 5.0 mg/kg for weathered gasoline and diesel fuel, respectively (Robbins, 1996:3-10). Hermon-Cruz reports detection limits ranging from 50 ppb to 200 ppb, with dynamic ranges commonly

ranging from 0 to 2,000 ppm (Hermon-Cruz, 1991:7). Bristol and others reported soil concentration detection limits on the order of fractions of a mg/kg, relative to detecting a headspace concentration on the order of 0.2 ppmv (Bristol et al, 1989:93).

FRTR reports the following limitations (FRTR, 1998): the instrument is not suitable for detection of most SVOCs; the instrument indicates if VOCs are present, but does not identify specific compounds from mixtures; the instrument may give false positive readings for water vapor and rain may affect operational performance; high humidity can cause lamp fogging and decreased sensitivity, which can be significant if soil moisture is high or if a soil gas well is in groundwater; high concentrations of methane can cause a downscale deflection of the meter; and, rapid variations in temperature at the detector, strong electric fields, and naturally-occuring compounds, such as terpenes in wooded areas, may affect instrument response.

Robbins reported the PID is susceptible to quenching (reduction in detector response) if condensation of water vapor occurs in the PID ion chamber (occurs when instrument temperature is less than sample temperature), high concentrations of organic vapors are present, non-detectable alkanes are present (e.g. butane, methane), and/or high levels of carbon dioxide are present (Robbins, 1996:3-7).

Fitzgerald reported a response reduction as high as 40 percent for benzene due to elevated atmospheric humidity (Fitgerald, 1992:57). Hermon-Cruz reported that 90 percent relative humidity appears to decrease the response of the 10.2 eV lamp PID by a factor of 2 for most compounds tested, relative to the response under dry conditions (Hermon-Cruz, 1991:4).

Minimum sample preparation is required to use a hand-held PID, although if ambient temperatures are low (below freezing), the samples may require heating to encourage analyte volatilization (NHSRC, 1998:M1-7). NHSRC reports the standard operating range of the PID is approximately 20 degrees Fahrenheit to 110 degrees Fahrenheit, although problems have been encountered when temperatures are at or below freezing (NHSRC, 1998:M1-11).

Specificity in photoionization analysis depends on the sensitivity of the detector to the species being measured, the number of interfering species, and the concentration of the species being measured relative to interferences (Hermon-Cruz, 1991:14). Interpreting the meaning of the response of a PID is the major difficulty when complex mixtures of chemicals are detected, thus, knowledge of the analytes potentially present and determination of the influences governing detector signals are critical in the interpretation of the readings (Hermon-Cruz, 1991:4).

Colorimetric Indicators. Colorimetric indicators cover a wide range of technologies and analysis platforms, but two common principles include titrimitry and colorimetry. Titrimetry is a wet chemistry procedure by which a solution of known concentration (a standard solution) is added to a water sample or soil-solute extract with an unknown concentration of the analyte of interest until the chemical reaction between the two solutions is complete (the equivalence point of titration) (EPA CERI, 1993:10-47). Titrimetry requires an abrupt change in some property of the solution at the equivalence point, which is typically indicated by a change in color produced by an added dye or by monitoring changes in pH or similar properties with a meter (EPA CERI, 1993:10-47).

Colorimetry involves mixing of reagents of known concentrations with a test solution in specified amounts, reaction of analytes with a test strip or reagent-phase platform, or reaction of analytes with a solid phase within a tube or collection container, that result in chemical reactions in which absorption of radiant energy (color of the solution, strip, solid) is a function of the analyte of interest and the analyte concentration (EPA CERI, 1993:10-47). Filter photometers can be used for many routine methods that do not involve complex spectra, while precise quantitation is commonly performed with spectrophotometers (EPA CERI, 1993:10-47).

Many of the kits and materials employ common reaction methods, including the Friedel-Crafts reaction, the Fenton's reaction, and the Fujiwara reaction. The Friedel-Crafts reaction is based upon an alkylation reaction for color formation (NHSRC, 1998:M1-19). Fentons reaction involves the production of hydroxyl radicals by reduction of hydrogen peroxide and iron (II), with the radicals attacking and hydroxylating particular analytes (Steinberg and Walker, 1995:3772). The Fujiwara reaction incorporates the reaction of germinal species with pyridine in the presence of water and hydroxide ions to form a visible light absorbing product (NHSRC, 1998:M1-28).

Resource Requirements. EPA OUST reported costs ranging from $17 to $42 per sample, depending upon the analyte and matrix (EPA OUST, 1999). NHSRC reported that indicator tube kits cost approximately $35 to $75 per box of 10 tubes, and the accompanying pump costs approximately $300 to $400 (NHSRC, 1998:M1-17). They report the cost of chemical colorimetric test kits is approximately $1,000 for soil or water matrix analysis, reagents for aromatics in water for 30 samples costs approximately $400, and reagents for aromatics in soil for 30 samples costs

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approximately $500 (NHSRC, 1998:M1-20). In addition, a reflective photometer may also be purchased for approximately $5,000.

NHSRC reports costs ranging from $8 to $14 per kit for chlorinated organics test kits, and the supplemental chloride-specific electrode can be rented for approximately $500 per month or purchased for approximately $3,500 (NHSRC, 1998:M1-24). They report a cost of $700 for soil hydrocarbon contamination test kits, which includes a digital analyzer, a balance, calibration standards, and enough reagents to perform 10 tests (NHSRC, 1998:M1-26). Replacement reagents cost between $10 and $15 per test.

NHSRC reports a cost of a colorimetric sensor for TCE and total trihalomethanes (THM) in water (and with different attachments, can be used for BTEX and PCE) of $2,500, while additional reagent caps (one test each) cost approximately $35 (NHSRC, 1998:M1-28). Colorimetric test kits for pentachlorophenol (PCP) in soil and water, TNT in soil, and polynuclear aromatic hydrocarbons (PAH) in soil were reported to cost approximately $40 to $50 per sample (NHSRC, 1998:M1-30).

EPA OUST reports a sample analysis time ranging from 10 minutes to 20 minutes, depending upon the type of test, the matrix, the analyte, and the kit manufacturer (EPA OUST, 1999). FRTR reports the turnaround time per sample is on the order of minutes (FRTR, 1998). NHSRC reports the analysis time for chemical colorimetric field kits for aromatics requires approximately 7 to 10 minutes per sample (NHSRC, 1998:M1-20). They report that it is possible to complete an extraction and analysis in less than 10 minutes for the chlorinated compound kits, and a sample throughput of 50 samples per day is achievable (NHSRC, 1998:M1-24). For the hydrocarbon test kit, extraction, settling, filtration, development, reaction, and analysis require approximately 25 minutes

per sample, although if performed in batch, 20-25 samples can be analyzed per hour (NHSRC, 1998:M1-26).

Cramer and others utilized a flow-injection system technique for the colorimetric determination of dissolved vanadium in natural waters. They reported a sample collection and analysis time of approximately 9 minutes (Cramer et al, 1997:528). Jenkins and Thorne tested a field method for quantitation of ammonium picrate (major component of many high explosives) and picric acid in soil and water. They reported single tests can be performed in approximately 20 minutes, and multiple samples can be processed in less time using cartridge or membrane manifolds (Jenkins and Thorne, 1995:10). Extraction and analysis times reported for the PCP, TNT and PAH kits required approximately 20 minutes to 30 minutes (NHSRC, 1998:M1-30).

Data Quality. Data quality produced by colorimetric indicators ranges from qualitative to quantitative. Qualitative data are produced with detector tubes and test kits when color changes are determined, signifying the presence or absence of the analyte or analyte group of interest. Using standards and calibration protocols in conjunction with instrumentation such as spectrophotometers, quantitative data can be derived from the intensity of color change, degree of transmittance, degree of reflectance, or similar method.

NHSRC reported the results from an EPA SITE demonstration utilizing chlorinated compound kits in the detection of PCBs in soils. Using the kits and the chloride-specific electrode for analysis of 87 samples against semi-quantitative constraints (e.g. concentration greater than or less than 50 ppb), an r of .92 (y-intercept of

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26.6 mg/kg, slope of 0.84) was produced when compared to laboratory results (NHSRC, 1998:M1-25).

Ivanov and Morozko utilized colorimetric methods in the quantitation of copper (II) and zinc (II) in aqueous solution. They reported correlation of colorimetry measurements and lab measurements for copper (II) and zinc (II) in untreated aqueous samples produced correlation coefficients of 0.990 and 0.987, respectively (Ivanov and Morozko, 1997:780).

Steinberg and Walker performed colorimetric analysis to determine benzene concentrations in water and aqueous soil extract. Even in the presence of numerous other aromatic compounds, their method produced an r of 0.99 for benzene in aqueous solution (Steinberg and Walker, 1995:3777). Jenkins and Thorne reported correlation of 0.90 between field and laboratory measurements of picrate in soil and water matrices (Jenkins and Thorne, 1995:9).

Ivanov and Markov reported RSDs of 13.6 percent and 8.8 perecent for the field tests for copper (II) and zinc (II), respectively (Ivanov and Markov, 1997:782). Cramer and others reported an RSD of approximately 1 percent for eight replicate samples (Cramer et al, 1997:528). Jenkins and Thorne report the precision of the picrate screening method in soil is approximately +/- 15 μg/g (Jenkins and Thorne, 1995:14). Muradov reported a precision of +/- 5 percent for the colorimetric detection of nitroglycerine via field spectrophotometer (Muradov, 1994:391).

Method Limitations. FRTR reported detection limits for chemical colorimetric kits of 10 ppm to 100 ppm for analytes in a soil matrix and 0.5

ppm to 10 ppm for analytes in an aqueous matrix (FRTR, 1998). For ex-situ detector tube analysis, FRTR reported the same detection limits as listed above (FRTR, 1998).

NHSRC reported that most indicator tubes have detection limits in the ppm range, while a few can detect compounds down to the mid-ppb range (NHSRC, 1998:M1-17). NHSRC reported typical detection limits for many VOC and PAH test kits are 1.0 mg/kg for soil, with a dynamic range of 1.0 mg/kg to 1,000 mg/kg, and 0.10 mg/L for water, with a dynamic range of 0.10 mg/L to 20 mg/L (NHSRC, 1998:M1-19). Additional test kits specific for chlorinated compounds have a detection limit of approximately 5.0 ppm when used in conjunction with the chloride-specific electrode.

NHSRC reported detection limits for some soil hydrocarbon test kits at approximately 20 ppm for heavier hydrocarbons (such as oil and grease) up to 200 ppm for lighter fuels (such as JP-4) (NHSRC, 1998:M1-27). Steinberg and Walker reported a detection limit of 0.1 ppm for benzene in water or aqueous soil extract, incorporating the use of a UV/visible spectrophotometer (Steinberg and Walker, 1995:3780). Jenkins and Thorne reported an MDL of 1.3 µg/g (~ 1.3 ppm) for ammonium picrate in soil and 3.6 µg/L (~ 3.6 ppb) in water (Jenkins and Thorne, 1995:7,8).

EPA reported that limitations in using colorimetric test strips for explosives (TNT, RDX, HMX) include possible intereferences caused by nitrite and the requirement to create a slurry if testing for analyte in a soil matrix (EPA FASCT, 1997:10).

Jenkins and Thorne reported that the water-acetone mixture percentage greatly affected the extraction efficiency of explosives from soil (Jenkins and Thorne, 1995:5). In addition, they noted that explosive transformation products create potential

interferences as do the presence of humic acids and humic materials in the matrix sampled (Jenkins and Thorne, 1995:7).

FRTR reported the following limitations: the procedure is time-consuming if a large number of samples must be analyzed; each analyte of interest requires different reagents and test procedures; and, samples with a wide variety of contaminants may give false positive results (FRTR, 1998). In addressing detector tubes, FRTR reported that the accuracy of the detector tube measurements are greatly affected by the flow rate and volume of air drawn through the pump (FRTR, 1998).

NHSRC reported if a petroleum release consists primarily of highly refined alkanes (i.e. no aromatics), errors underestimating contaminant concentrations can be made if the operator is not aware of the substance type (NHSRC, 1998:M1-21). This can be resolved by recalibration of the sample with the appropriate substance-specific calibration photograph.

For chlorinated hydrocarbon detection kits, contaminant degradation daughter products, chlorinated organics similar in molecular structure, and inorganic chlorides can potentially create interferences (NHSRC, 1998:M1-24). Many of the semi-quantitative test kits are designed to be conservative, and thus will result in false positives. For PCB test kits, other sources of organic chlorine, such as chlorinated solvents or pesticides, have the potential to cause false positives, while many kits will respond differently to the different Aroclors because they have differing degrees of chlorination, potentially overestimating or underestimating the degree of contamination at a site (NHSRC, 1998:M1-24).

NHSRC reports that for many tests utilizing instrumentation which determines concentrations through transmittance or reflectance, the presence of turbidity can cause severe error in analyte quantitation (NHSRC, 1998:M1-26). In addition, false positives may occur if naturally-occurring waxes and oils are present in the sample. In many of the methods, the analyte being tested for must be known so that the user can choose the correct calibration, otherwise, a conservative calibration can be used, which provides an approximate concentration of analyte or analyte group present (NHSRC, 1998:M1-27).

Emerging Site Characterization Technologies. Emerging site characterization technologies with promise for potential future use at DoD installations in the ROK include the following: the Environmental-Field Assessment and Survey Technology (E-FAST), developments in capillary electrophoresis, direct push platforms and VOC detection (primarily halogenated VOCs), direct push platform vision probe system, the sonic cone penetrometer, and the cone penetrometer and X-ray fluorescence. We will also overview potential detection methods and sensor suite development initiatives for the Geoprobe and CPT in this section.

Environmental Field Assessment and Survey Technology. In 1995, the USAF Research Laboratory solicited innovative concepts for sensors, sensor integration, and data analysis for site characterization and monitoring (AFRL, 1998). One response was a proposal to integrate environmental sensor, video, audio, position, communication, encryption, and bar-code reader technologies. The result is a field portable device for data collection, tagging, analysis, and multimedia reporting consistent with U.S. federal requirements for data integrity and user desires for cost effectiveness (AFRL, 1998).

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The initial device will include a miniaturized surface acoustic wave environmental sensor integrated on a Personal Computer Memory International Association (PCMCIA) Card. Detection limits of less than one part per million for VOCs have been demonstrated in the laboratory with this technology (AFRL, 1998). E-FAST is expected to provide a versatile, field-portable data acquisition and analysis device with data storage, retrieval, and transfer capability (AFRL, 1998). The incorporation of RBCA software will permit site assessments in real-time. The use of open architecture, standard protocols, and commercially available components will allow easy incorporation of added capabilities in the future as they emerge. An illustration of the system conceptual design is shown in Figure 3.
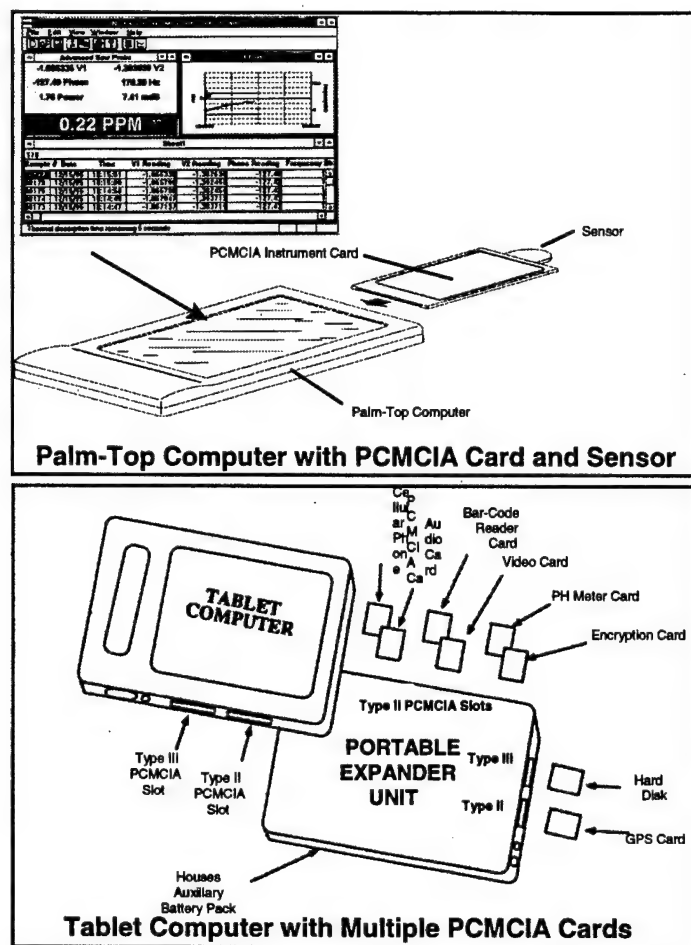
Figure 3. E-FAST System Conceptual Design

Capillary Electrophoresis. Electrophoresis is a process in which charged

species (ions or colloidal particles) are separated based upon differential migration rates

in an electrical field (Leary and Skoog, 1992:675). Electrophoresis dates back to the

1930's, however, more recent modifications to the basic technique include capillary

electrophoresis (CE), capillary zone electrophoresis (CZE), and high performance

capillary electrophoresis (HPCE). In CE methods, components of a mixture (such as

contaminated groundwater) are transported through a horizontal capillary tube by high dc

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potential that is imposed across the length of the tubing (Leary and Skoog, 1992:676). CZE, also known as free zone electrophoresis, is a separation that is based on the tendency of mixtures of ions to separate into sharply-defined zones of identical ions, again under a high dc potential, which then migrate at a unique velocity as a result of their characteristic mobility (Brumley and Gerlach, 1999:45).

Electrophoresis separations arise from differences in mobilities of solutes. Electrophoretic mobility is proportional to the charge on the solute and inversely proportional to the frictional, or retarding, forces that are determined by the size and shape of the solute species as well as the viscosity of the medium (Leary and Skoog, 1992:677). Solvent properties, such as ionic strength, pH, and dielectric constant are also important because they affect the effective charge on the solute and, for larger molecules, their shape and hydrodynamic size (Leary and Skoog, 1992:677).

CE or CZE is normally utilized in conjunction with a detector (as it is a separation technique). CZE is easily interfaced with optical detection methods (such as UV-VIS absorption), indirect detection (based on UV or fluorescence), or LIF, where on-column detection is usually carried out (Brumley and Gerlach, 1999:45). Detection limits reported using CZE-UV ranges from approximately 10 ppb to 1 ppm, while CZE-LIF ranges from approximately 1 ppt (part per trillion) to 10 ppb (Brumley and Gerlach, 1999:46).

While a field instrument or field-based method employing CZE-detector technologies has not been deployed, these technologies are showing great promise in the laboratory. Brumley and Gerlach report that CZE-LIF combines a very powerful separation technique and a very sensitive detection technique, thus providing improved

selectivity, reliability and detection limits over many alternative methods. CE technologies, both established and emerging, allow detection and quantification of the spectrum of environmental contaminants, from dissolved inorganic cations to polynuclear aromatic compounds.

Direct Push Platforms and VOC Detection. One of the major limitations of the cone penetrometer (SCAPS and ROST™) and percussion probe (Geoprobe®) systems is the inability to detect most VOCs (primarily halogenated VOCs). Several new technologies are being developed, tested and fielded in an effort to provide VOC detection capability for direct push platforms.

Geoprobe® Platform with Hydrosparge System. The USACE utilized a Geoprobe® system for downhole sensing of VOCs. The Geoprobe® system is a percussion driven soil probe, unlike the cone penetrometer system which utilizes the mass of the truck to hydraulically "push" the probe into the subsurface. The Geoprobe® has an average rate of advancement of one foot per minute, resulting from the probe receiving approximately 30 blows per second, with approximately 50,000 pounds of force per blow (Christy, 1998). Normal operating depths for the Geoprobe® system (depending upon system model) are approximately 60 to 120 feet.

A VOC-contaminated site was disCVered at a facility located on Aberdeen Proving Ground, a United States Army (USA) research test and evaluation center located 20 miles northeast of Baltimore, Maryland. Activities at the facility included cleaning large gun barrels and military rolling stock, which required the use of large quantities of solvents and petroleum products (USACE, 1997:1).

The sampling and analysis plan incorporated the Geoprobe® SCAPS platform in conjunction with a hydrosparge system (HS), which consisted of a hydropunch (HP) temporary well, an in-situ sparge (ISS) device, and an ion-trap mass spectrometer (ITMS) (USACE, 1997:6). The normal operating procedures for the HS system of investigating groundwater contamination include first accessing the groundwater using an HP-installed well (expedient well). Once the well is installed and the water level stabilizes, the ISS system is lowered into the well, where it purges the VOC analytes in-situ from the groundwater using helium gas. The analyte stream was directly interfaced to the ITMS, and the VOC contaminants analyzed. The ITMS is capable of both qualitative identification of analytes based on their mass spectra and of quantitative measurement based on the intensities of analyte-specific ions in the mass spectra (USACE, 1997:9). This method provided correlation coefficients (r) between laboratory analysis and HS system analysis of .975 (slope of 1.20, y-intercept of 6.0) for TCE and .990 (slope of 0.85, y-intercept of –4.0) for TCA, respectively (USACE, 1997:19). In general, the method provided field results that correlated well with laboratory analyses over contaminant concentrations spanning three orders of magnitude.

Geoprobe® Platform with Permeable Membrane Sensor.
Detection of VOCs has been demonstrated through the use of a membrane interface probe (MIP) in conjunction with the Geoprobe® platform (Christy, 1998). VOCs in the subsurface come in contact with the heated surface of the MIP ploymer membrane, where they then diffuse into the membrane. VOCs in the gaseous, dissolved, solid or free product phases diffuse into the membrane, while bulk fluid (e.g. water, air), either gases or liquids, do not travel across the membrane (Christy, 1998). The MIP membrane is

heated (80 to 125 Celsius) to enhance VOC diffusion and partitioning processes. After diffusing across the membrane, the VOCs partition into the carrier gas, which sweeps the backside of the membrane. Transport of the VOC-laden carrier gas to the detector (located at the ground surface), for a theoretical 100 foot tube length, requires approximately 35 seconds (Christy, 1998). Common detectors include the PID, the FID, the GC-PID, the GC-FID, and the GC-ECD. Depending upon detector configuration, qualitative to semi-quantitative data can be produced with this system.

Currently, the primary use of the MIP has been determining the distribution of chlorinated solvents in source areas (Christy, 1998). The detection limits for most of the chlorinated species using the MIP-FID or MIP-PID is approximately 5 ppm. However, the MIP system combined with soil conductivity and resistivity measurement capabilities provides a powerful logging tool that yields a wealth of information about subsurface lithology and VOC contaminant distribution.

Geoprobe®/CPT Platform and Negative Ion Sensors. The negative ion sensor systems being developed for use on the Geoprobe® or cone penetrometer platforms is based upon contaminant capture fundamentals similar to the MIP previously described; however, the sensor location and configuration are different. VOCs (this research primarily directed at halogenated VOCs) in the soil formation are sampled through a heated microporous inlet membrane (MPIM). A carrier gas sweeps the vapors into the detector, which is located in the interior of the direct push probe (versus at the ground surface). Reported advantages of having the detector in this downhole configuration include no transit time lag or dilution of vapor concentrations,

avoidance of adsorption losses in the transfer line, and avoidance of carryover or bleed of analyte from the transfer line after a "heavy hit" (Dakota Technologies, 1998).

Numerous detector configurations were tested by Dakota Technologies, including a halogen-specific detector (HSD), a PID, and a photoemissive electron capture detector (PE-ECD). The ideal detector would provide sensitive, specific and fast response to VOCs with minimal response/interference from nonhalogenated VOCs, water, and oxygen (Dakota Technologies, 1998).

HSD operation is based upon chlorinated compounds in the analyte stream decomposing when they encounter a heated (800 to 1200 Celsius) ceramic surface that is doped with an alkali metal (Dakota Technologies, 1998). As the chloride atoms thus formed re-contact the ceramic surface, they extract electrons to form gaseous chloride ions, which are drawn to a biased node and quantitated as a current. Dakota Technologies reported that modifications to the "off-the-shelf" HSD sensors in order to permit downhole use were fairly straightforward, and quantification of TCE was relatively accurate. The major uncertainty about the HSD is the possible long-term effects of the high operating temperature on the electronics or elastomer retaining rings (Dakota Technologies, 1998).

Although the PID does not provide specific response to individual VOCs, several benefits were evident in fielding a downhole version. Besides field screening, downhole PID is convenient for assessing test procedures, resolving integration issues, and field testing control and data acquisition (Dakota Technologies, 1998). Results from initial downhole PID laboratory tests were reported as encouraging, and planned improvements are expected to bring the sensor to near equivalence with existing commercial detectors.

ECDs are the GC detectors of choice for detection of chlorinated organic compounds (including many SVOCs) and nitro-organics (e.g. explosives). Thus, a PE-ECD prototype was tested with both a GC and a MPIM. The sensor consists of a microsecond duration flash lamp, a gold-coated metal window that serves as the photoelectric surface, a simple collector, and a digital oscilloscope. The promise of the PE-ECD concept has been established, but compared to the HSD, it is more complicated to operate, it is susceptible to oxygen interference, and it exhibits a wide range of responses for different chlorinated species (Dakota Technologies, 1998). However, Dakota Technologies is improving on the initial concept in order to provide greater sensitivity, easier miniaturization, and lower capital costs in order to make the PE-ECD competitive with the HSD.

Direct Push Platform Vision Probe System. Traditionally, in order to obtain detailed information about subsurface soil characteristics, it has been necessary to collect soil samples and transport them to the laboratory. This approach lends itself to quite limited spatial resolution of small-scale variations in soil properties. The need for a means of documenting soil properties on very small spatial scales (1 cm or less) became apparent during studies of the effects of soil type on the response of cone-penetrometer deployed, spectroscopic-based, optical sensors for real-time in-situ field screening of chemical contaminants in soils (Knowles and Lieberman, 1998:128). This method of characterizing soil type provides data on the same spatial scales as the spectroscopic measurement (i.e., 1 cm or less), thus providing a better method of accounting for the effect of variations in soil type on the optical chemical measurement. Such a method provides a means of improving the quantification of spectroscopic measurements, and

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can be used to directly measure key variables, such as soil particle size distributions, that are important for determining subsurface transport properties (Knowles and Lieberman, 1998:128).

Indeed, current conceptual models of dense non-aqueous phase liquid (DNAPL) transport suggest that when sinking DNAPL encounters a confining layer, the DNAPL may accumulate in a "pool" and then spread laterally until it finds a fracture or some other path to a deeper zone (Anderson et al, 1998). This mode of transport through the subsurface leads to very heterogeneous distributions of residual product that are almost impossible to delineate. A video microscope-equipped probe would help to address this need for a method to detect widely dispersed micro-globules of residual free product (Anderson et al, 1998).

Considerable research is being performed with the goal of fielding a probe equipped with a video microscope, in conjunction with other analyte detection sensors, for employment by the direct push platforms. Hryciw and Raschke described one variation of a new "vision cone penetrometer" (VisCPT) which acquires video images of the subsurface continuously with depth as it is pushed into the ground. Besides addressing one of the primary limitations of the direct push platform, the inability to directly observe the soil, the VisCPT also allows changes in stratigraphy, precise location of interfaces between soil layers, and small-scale subsurface anomalies such as clay seams, sand lenses, fissures, etc., to be identified (Hryciw and Raschke, 1997:1074).

Knowles and Lieberman report that the video microscope system consists of a miniature charge-coupled device color camera coupled with appropriate magnification and focusing optics to provide a field of view with a coverage of approximately 2 m

(height) by 3 mm (width) (Knowles and Lieberman, 1998:128). The camera/optic system is mounted in a direct push probe so that the camera views the soil that is in contact with a sapphire window mounted on the probe. A reported push rate using this system is approximately .17 cm/s, which is considerably slower than the standard probe advancement rate (Anderson et al, 1998). The soil outside the window is illuminated by diffuse light provided through the window by an optical fiber illumination system connected to a white light source at the surface. The video signal from the camera is returned to the surface where it can be displayed in real-time on a video monitor, recorded on a video cassette recorder, and/or captured digitally with a frame grabber installed in a microcomputer system (Knowles and Lieberman, 1998:128). Images for several system variants are acquired continuously at a rate of approximately 30 image frames per second (Hryciw and Raschke, 1997:1076).

Field results have proven the system quite beneficial. Anderson and others utilized a vision probe at six locations to produce clear images of finely dispersed micro-globules of NAPL contaminant (Anderson et al, 1998). These images along with other sensor data were used to pinpoint soil and water sample locations and depths. Knowles and Lieberman reported results from three locations, demonstrating the ability of the camera to discriminate small-scale vertical variability in soil type and even to observe water and NAPL ganglia in the soil matrix of the saturated zone (Knowles and Lieberman, 1998:130). Initial field results also showed that the system was capable of revealing differences in soil color, which may provide insight into variations in soil minerology. Hryciw and Raschke reported that the system was rugged, no scratching of the sapphire window was observed, no soil smearing was observed (even when passing

through saturated, fine-grained soils), and the images were well lit, in crisp focus, and very stable (Hryciw and Raschke, 1997:1076).

Many system improvement opportunities have been identified and are under development. Two such developments are briefly discussed. With the present lens system, the minimum particle size that can be resolved is on the order of 10 μm (Knowles and Lieberman, 1998:130). In order to extend the capability of the video microscope system to discriminate either larger or smaller particles, a second camera system with its own lens system or a single camera with a zoom lens system could be used to provide a variable magnification factor. Efforts to evaluate the feasibility of using image processing techniques to extract parameters such as soil particle size distributions from the images are also under development. Preliminary results from a procedure that uses an edge detection scheme to discriminate particles in order to estimate particle size distributions compared quite well with a standard sieve/hydrometer analysis (Knowles and Lieberman, 1998:130).

Sonic Cone Penetrometer. Existing cone penetrometers are capable of penetrating soft clays and normally consolidated sands to depths of approximately 100 feet to 150 feet. Achieving the required depth of penetration has been difficult in many geologies that are either cemented, over-consolidated, or gravelly in nature. Integration of the sonic technology with conventional CPT promises to significantly improve the achievable depth, speed, versatility, and cost of sensing for site assessment and monitoring (ARA, 1998).

As stated, the sonic system is an addition or complement to the standard CPT platform. The system operation principle is to utilize two eccentric masses, spun at high

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speed, in order to transfer vibrational energy along the push rod (energy transferred from surface down to probe tip) to permit more efficient aquifer penetration. Primary system components include a sonic head (containing two eccentric masses and two hydraulic motors contained in a housing), a push rod clamping system, vibrational isolators, a push rod guide tube, push-pull cylinders, and a reaction plate (Nielsen, 1998).

Testing of the sonic CPT has been conducted at several locations. Applied Research Associates, Inc. (ARA), reported that at a site where traditional SCAPS-CPT encountered refusal at 20 feet below ground surface (bgs), the sonic CPT was utilized and penetration was accomplished (ARA, 1998). At another site, a target depth of 100 feet was achieved after encountering in excess of 10 refusal layers. This was achieved through the alternation between static mode (normal CPT push) and sonic modes (sonic system engaged). ARA also demonstrated that the sonic mode reduces required push force by up to 80 percent, while not significantly increasing probe tip temperature (which was thought to be a possible concern) (ARA, 1998). At yet another site, a CPT probe was pushed in static mode to 156 feet, where it encountered a green clay refusal layer. Sonic mode was engaged to penetrate the layer, and static mode was then utilized to achieve the target sampling depth of 183 feet bgs. Nielsen reported successful demonstration of the sonic CPT at sites containing caliche soil, difficult glacial gravels and cobbles, and deep sites with numerous clay refusal layers (Nielsen, 1998).

A summary of reported benefits of the system include the following (ARA, 1998):

1. Allowed greater penetration depths using standard CPT rod geometries (1.44 and 1.75 inches diameter) on existing CPT platforms;

2. Enabled the use of larger probe diameters, designed for greater sensor capacity;

3. Improved the ability of medium and lighter duty CPTs to penetrate difficult soils; and,

4. Enabled the placement of larger diameter (3 inches or greater) wells by CPT.

Cone Penetrometer and X-ray Fluorescence. The development of sensors designed for on-site in-situ analysis using CPT for inorganic elements, particularly heavy metals, is an area that is largely untapped. The techniques for inorganics that have been devised are not nearly as well developed nor have they been field tested as much as samplers and detection schemes for organic compounds (Aldstadt and Martin, 1997:12). One potential in-situ inorganic detection method is XRF. The specifics concerning operational principles and analyte detection methods were previously discussed. Research focus is directed toward incorporating an XRF system in a direct push platform probe.

The key components in the proposed design for a miniaturized XRF sensor in the confined space dictated by the CPT rods include a commercial X-ray tube of approximately 25 mm in diameter, collimating apertures, an X-ray filter, a miniaturized high voltage power supply, and an energy-dispersive detector (lithium-drifted silicon diode electrically cooled by Peltier coolers) (Aldstadt and Martin, 1997:14). The material used for the excitation and emission collection windows is of particular importance as well, with boron carbide being suggested as a suitable candidate with respect to X-ray transmissivity, resistance to abrasion, reasonable cost (versus diamond), and the ability to

withstand pressures encountered during a penetrometer push (Aldstadt and Martin, 1997:12).

Of primary concern is whether the system will meet suitable limits of detection and provide reasonable accuracy. Initial results of prototype systems have shown detection limits of 10 ppm to 100 ppm for metals in various soil matrices, while accuracy was on the order of 10 percent if a standard with a similar matrix was used. Accuracy degrades to 50 percent when standards of a dissimilar matrix were used (Aldstadt and Martin, 1997:15). Although preliminary work has established that only minor modifications to existing technology are necessary to assemble the XRF in a direct push probe configuration, the issues of accuracy and sensitivity require further study, while the ruggedness of the source and collection optics in the field environment also require further evaluation.

Detection Methods and Sensor Suite Development Initiatives. As shown by the emerging technology information presented to this point, a great deal of research is being focused on evaluation of analyte detection methods for application with direct push technology platforms. A variety of currently available and developing sensing technologies were evaluated by Dakota Technologies, Inc., (DTI) for feasibility of adaptation for use with direct push probes. This section will provide some basic background information concerning in-situ applications and then discuss analytical methods considered for potential use.

Background. Development of sensors capable of being deployed downhole presents many challenges. Concerns over size, ruggedness, power requirements, and cost present technical challenges that require careful planning and a

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clear objective of what is desired for field use. Contaminants can exist in a variety of matrices, and each of these matrix types, coupled with contaminant phase, affect contaminant recovery and may affect instrumental response during detection. Successful methods must account for this myriad of factors and still provide rapid, cost-effective, high quality data. In-situ measurements are commonly categorized as either uphole measurements or downhole measurements. Uphole measurements are defined as directing a collection probe into the subsurface, gathering the desired contaminant analyte, and transporting the contaminant back to the surface for analysis (e.g. application of the Geoprobe® MIP method), while downhole measurements are defined as directing the instrument into the subsurface, performing measurements while in-situ, and transporting data back to the surface (e.g. application of LIF) (DTI, 1996:5).

In-situ detection methods can be divided into descriptive categories relevant to their mode of operation, including continuous, stepped, and one-time monitoring modes (DTI, 1996:5). Continuous operation is based on a means of making an "on-the-fly" measurement as the probe is continuously being driven into the subsurface. Stepped or discrete measuring is based on pausing the advancement of the probe and taking a measurement, and then proceeding with the advancement upon completion of the measurement. A one-time mode of operation is the case when the probe is driven into the subsurface and used to make a single measurement.

Spectroscopic Methods. The spectroscopic methods reviewed for potential use with the direct push platform include LIF, Raman spectroscopy, photoacoustic spectroscopy, infrared (IR) spectroscopy, attenuated total reflectance (ATR) spectroscopy, multiphoton ionization (MPI), and atomic emission/fluorescence

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spectroscopy--laser induced breakdown spectroscopy (LIBS). LIF has been previously discussed and will not be included within this section.

Raman spectroscopy is based on the ability of molecules to inelastically scatter incident light at wavelengths less than (Stokes), equal to (Rayleigh), or greater than (anti-Stokes) the incident wavelength (DTI, 1996:7). Raman spectroscopy is based on the nonlinear interaction of incident radiation with a given analyte and can be used to fingerprint molecules or functional components of molecules. However, DTI reported that the insensitivity of the Raman signal does not currently make it a viable and encompassing method for analyte detection (DTI, 1996:7). In addition, high incident intensities are required which can result in breakdown of the silica material of the fiber optic cable. Efforts are underway to explore optimal methods of using Raman spectroscopy.

Photoacoustic spectroscopy provides spectra of solids, semi-solids, turbid liquids, or gases (DTI, 1996:8). Modulated UV or visible radiation is directed into a sample or gas chamber and absorbed. The absorbed energy is converted into an acoustic wave with periodicity of modulation. The resulting changes in static pressure are monitored with a microphone, and the signal used to identify substances. A primary advantage of this technique is the ability to monitor opaque or heavily scattering matrices that are not readily monitored using standard optical techniques (DTI, 1996:8). In addition, a simple UV-Vis spectrum can readily be obtained by tuning the excitation laser and monitoring the photoacoustic signal. Research is on-going in this area.

IR spectroscopy is a common and versatile analytical method that can be applied to a variety of molecular analytes in a variety of phases. IR spectroscopy is used to probe

the vibrational energy levels of molecules in the 400 cm^{-1} to 4000 cm^{-1} frequency range (DTI, 1996:8). Fourier Transform IR (FTIR) spectrometers can be adapted for liquid, gas, solid and surface matrices. Analyte species are identified by the presence of certain wavelength absorbing functional groups and by 'fingerprint' regions at higher energies (DTI, 1996:8). IR absorption is used in a variety of in-situ applications, however, applications with solids or liquids are likely to present physical limitations or scenarios where the energy is completely absorbed and does not impinge on the detector. Thus, the likelihood of a downhole IR detector is not encouraging, although FTIR may have promise in an uphole configuration. By delivering a soil gas via a probe to a mobile FTIR instrument with multi-pass capabilities, discrete or continuous spectra can be obtained which profile soil gas analytes. Research is on-going in this area.

ATR spectroscopy is a variant of traditional IR absorption. In ATR spectroscopy, light is directed into a transparent crystalline material at an angle that creates a series of internal reflections, and as the light propagates near the crystal surface, a portion of the light extends into the surrounding medium (DTI, 1996:9). The attenuation of this wave by light-absorbing species on the crystal surface can be measured and is the basis of ATR spectroscopy (DTI, 1996:9). The application of ATR to downhole measurements has received little attention due to the many challenges and limitations. These include the observation that water soluble crystals must not be used for light propagation and a proper purge and filtration system must be employed to reduce particulate matter and adequately discharge the sample after analysis (DTI, 1996:9). The requirement that light be incident and collected at pre-set angles to the ATR material presents a technical challenge while the need for spectral databases and spectral calibration as per the angle of

incidence do not lend to desired in-situ use of this method. No further research is mentioned in this area.

MPI is currently being pursued as a gas-phase detection system for BTEX species. MPI operates on the principle that two visible photons are required to ionize BTEX molecules (DTI, 1996:10). The macroscopic degree of ionization is directly proportional to the absorptive cross-section of the BTEX species. The greater the absorption, the greater the probability that a species will absorb two photons and ionize, thus, a measured ionization current is proportional to the absorption spectrum of the particular analyte or set of analytes (DTI, 1996:10). DTI has detected benzene concentrations down to 5 ppbv using a laboratory MPI instrument and they are adapting a prototype to fit the probe configuration. Currently, efforts are focused on integrating the MPI unit with a portable tunable laser source for downhole application.

The typical mechanism of atomic emission /fluorescence (AE/F) spectroscopic approaches involve breakdown of the analytical species into its atomic constituents, whereupon the constituents are excited and emit radiation commensurate with their electronic energy spacing. This works best for the metal species and Group I and II species of the periodic table of elements. Typical breakdown methods include flame, spark, inductively coupled plasma (ICP), or microwave digestion techniques (DTI, 1996:10). Once breakdown occurs, analyte determination can be made through measurement of absorption (constituent atom excitation) or fluorescence (constituent atom decay).

LIBS is gaining attention in regard to its potential for monitoring and detecting atomic species. In a downhole application, a fiber optic serves as the conduit for a laser

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pulse that is tightly focused outside the probe. This focused energy creates a plasma discharge, causing molecules in the matrix to break apart into excited atomic and ionic species (DTI, 1996:11). The emission from the discharge is collected with fiber optic(s) and directed into a filter (monochromator) for species delineation. LIBS is effective for detection of heavy metal species, but is not suited for detection of PAHs, chlorinated solvents, or BTEX species. Research is ongoing in this area.

Mass Related Methods. Mass spectometry (MS), as briefly discussed in a previous section, is based upon ionizing a particular analyte (preferably after separation) and using electric/magnetic fields to direct the charged analyte to a detector (DTI, 1996:11). The speciation inherent to MS arises from ionization and breakdown of the analyte. The resulting mass spectrogram of narrow, finger-like features is a fingerprint of a given analytical species. However, mass spectrographs are expensive, complex, require highly trained operators, and must be used in conjunction with a separation scheme (commonly GC) (DTI, 1996:11). Field applications of MS suffer from lower resolution and lower vacuum pressures, and its application to downhole scenarios is prevented by the size and sophistication of the method. No further research is mentioned in this area.

Harmonic Methods. Quartz crystalline microbalance (QCM) and surface acoustic wave (SAW) devices are sensitive detectors that can be custom designed for specific or general analyte detection. The governing principle behind these devices is the attachment of an analyte species to the surface of the quartz resonating surface, where the attached species proportionally dampen the harmonic motion of the device (DTI, 1996:11). The species is quantified by measuring the change in resonance frequency of

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the device. However, since detection occurs by the attachment/binding of an analyte to the resonance surface, surface-modified SAWs or QCMs must incorporate appropriate layering material that selectively binds the analyte(s) of interest (DTI, 1996:12). The sensitivity of these devices to small movements of air currents prohibits their use with downhole configurations.

Reaction-Type Sensors. Reaction-type methods/sensors explored included the Fujiwara reaction, and immunoassay. Immunoassay techniques were previously described and will not be included in this section.

The Fujiwara reaction is a selective chemical reaction between an organochloride (e.g. TCE) and pyridine. The premise behind the reaction is that the absorbance of basic pyridine is changed when it is exposed to various organochlorides (DTI, 1996:12). This change in absorbance results from the organochloride forming a chromophore with the pyridine molecules, and the fluorescence of the resulting chromophore is used to determine the presence and concentration of organochlorides. Reported difficulties with the Fujiwara reaction include loss of pyridine, inability to maintain pyridine pH, variations in water content, lack of sensitivity, and loss of dye color (DTI, 1996:12). Downhole applications result in remote, integrated responses to the presence of organochlorides. The response of the probe was limited by the diffusion rate of the analytes, and thus, lower analyte concentrations (such as those commonly present in environmental media) required significantly longer integration times. The difficulties of the trial probes are being addressed and development and testing of various membrane materials is being researched.

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Chromatographic Detection Methods. Detection methods related to chromatographic techniques included the electron capture detector (ECD), the PID, and the thermal conductivity detector. The PID was previously described and thus will not be addressed further in this section.

The ECD is a commonly used means of ionization detection. The ECD instrument consists of a small chamber coated with a radioactive nickel layer in close proximity to an anodic electrode. Beta particles (high energy electrons) are emitted from the nickel surface and collide with gas-phase analytes. Low energy electrons are emitted from the collision and are quickly gathered by the pulsed anodic electrode in which the current response is measured and analyte concentration determined (DTI, 1996:14). The ECD commonly follows a separation technique and identifies individual analytes as they elute from the separation method. ECD has unsurpassed sensitivity to the dichlorinated and polychlorinated species, although ECD is five to six orders of magnitude less sensitive to hydrocarbons, ethers, esters, and simple aliphatic species (DTI, 1996:14). The high differential sensitivity to dichlorinated and polychlorinated species and the relatively compact instrument size make the ECD a viable component of a preferential downhole sensor, while improvements in analyte/analyte class-selective permeable membranes will improve chlorinated hydrocarbon detection.

The thermal conductivity detector (TCD) instrument utilizes a universal, non-destructive, commonly used scheme by which the thermal conductivity properties of an analyte are used as a means of detection. The TCD measures the difference in thermal conductivity between a carrier gas (usually helium) and the analyte(s). This difference is translated into analyte concentrations. As with the ECD, this method commonly follows

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a suitable separation technique. While a candidate for miniaturization into a soil probing device, TCDs require block temperatures (commonly several hundred Celsius) and are generally sensitive to temperature change, while flow rate of the carrier gas must be carefully controlled (DTI, 1996:15). In addition, high temperatures beneficial to maintaining volatility of analyte species are detrimental to some instrument components (e.g. filament) and subsequently decrease instrument sensitivity and useful life (DTI, 1996:15). All these factors do not contribute to making the TCD a practical choice for downhole application. No further research is mentioned in this area.

Electrochemical Methods. Electrochemical methods rely principally on the ability of analytes to lose (by oxidation) or gain (by reduction) electrons during a chemical reaction. Analytes can be caused to interact quantitatively with electrical potentials and currents. The general categories of electrochemistry include electrogravimetry, conductimetry, coulometry, potentiometry, and voltammetry (DTI, 1996:16). Analytes that most readily undergo electrochemical reactions include the metal and metalloid species, and although a wide variety of instruments have been deployed, their requirements make them cumbersome and inefficient for application to downhole measurement (DTI, 1996:16). Many electrochemical methods require a high degree of maintenance and care in the preparation of electrodes, electrolyte solutions, and reaction conditions, while ensuring proper pH is maintained. A downhole, confined environment does not provide the general flexibility to efficiently account for these concerns. No further research is mentioned in this area.

Additional Methods. Additional methods explored for use in direct push probes include surface plasmon resonance (SPR) and cantilever

measurements. These two methods of analyte determination are relatively new even in the laboratory, but were reviewed for their potential as downhole measurement techniques.

SPR has been proposed as a means of measuring concentrations of chemical species in-situ. Sensors based on SPR utilize the activity of surface plasmons (i.e. charged centers localized on the surface of lattice networks) via spectroscopic means (DTI, 1996:18). Like the harmonic devices previously described, a thin film is placed on the surface of the plasmon device and is used to absorb chemical species to the surface. Changes in real time are thus monitored with the addition of chemical species. Although it appears as if cost, size, and simplicity are distinct advantages, questions concerning selectivity, sensitivity, and the need for consecutive measurements remain (DTI, 1996:18). Further research into material design and optical detection is required before this approach becomes viable for downhole measurements.

Cantilever measurement devices have traditionally been used as the "sensing" mechanism in atomic force microscopy (AFM). Cantilevers consist of an extended arm on the end of which a sharp, downward pointing tip rests (similar to a phonograph). In the generic AFM experiment, a resonating cantilever rests on the surface of a material and is moved about, while forces between the surface and the cantilever tip give rise to deflections of the cantilever that in turn are used to map out the topography of the surface (DTI, 1996:18). Similar to the SAW and QCM devices, the requirements for a coating dictates the class of analyte species detectable. The coating serves as a permeable barrier to selective analyte species that are embedded in the coating and affect the resonance of the cantilever arm (DTI, 1996:18). The potential array of cantilevers, each coated with a

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different analyte-specific coating, is envisioned to gather a database of information from complex mixtures. However, while applicable to downhole considerations, this method is currently a "one-shot" approach and does not provide for repeated use as the probe is advanced (DTI, 1996:19). Research on the development and refinement of this technology shows potential for future application.

D. Risk Assessment

Risk, according to Cohrssen, is defined as the possibility of suffering harm from a hazard (Cohrrsen and Covello, 1989:1). A hazard, which refers to a substance or action that can cause harm, is a source of risk (Cohrssen and Covello, 1989:1). Risk assessment, in general, refers to the technical assessment of the nature and magnitude of risk.

Because risk is ubiquitous, risk assessment methods can be used to analyze phenomena ranging from the number of excess cancers expected to be caused by the use of a new pesticide to the likelihood of a terrorist attack (Cohrssen and Covello, 1989:2). In this thesis, however, the emphasis is placed on evaluating risk to human health posed by exposure of personnel to hazardous waste sites at DoD installations in the ROK.

In discussing risk assessment, the author will introduce two concepts: traditional risk assessment and risk-based corrective action (RBCA). Traditional risk assessment procedures were developed to meet requirements set forth in CERCLA and the Superfund Amendments and Reauthorization Act (SARA), resulting in the traditional baseline risk assessment. Over time, these risk assessment procedures have evolved. Today, RBCA has become a prominent method of addressing risk at hazardous waste sites. While the roots of RBCA lie in addressing leaking underground storage tank sites, the approach has

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seen widespread adoption by federal, state and local regulatory agencies for application at sites with a variety of contaminants (Koch, 1996:39). In fact, the RBCA approach has become the standard approach for addressing contamination at Brownfields sites.

One risk assessment method and two RBCA methods will be discussed. These methods may be employed by DoD decision-makers in the ROK. These methods include the DoD Relative Risk Site Evaluation method, the American Society for Testing and Materials (ASTM) RBCA method, and the state of Hawaii RBCA method. The methods will be discussed in terms of conformance/parallels to DoD CONUS policy and requirements, required method inputs, and expected method outputs. Analysis of this information will allow DoD decision-makers in the ROK to evaluate and select the appropriate risk assessment/corrective action method that best meets their needs.

Traditional Risk Assessment. Risk assessment is a multidisciplinary method for estimating the probability and severity of hazards to human health, safety and the natural environment (Finkel and Golding, 1994:6). The ability to assess risks in a technically sound manner and to communicate such findings in a meaningful manner requires application of knowledge from a variety of disciplines. Risk assessments produce several complementary types of output, including numerical estimates of the magnitude of the assessed risk, quantitative descriptions of the type of adverse effect associated with the estimate of magnitude, and qualitative discussions of the knowledge base on which the predictions of hazard are made (Finkel and Golding, 1994:6).

Decision-makers must evaluate risk in terms of risk assessment and risk management. Risk assessment is the use of the factual base to define health effects of exposure of individuals or populations to hazardous materials and situations (NAS,

1983:3). Risk management is the process of weighing policy alternatives and selecting the most appropriate action, integrating the results of risk assessment with engineering data and with social, economic and political concerns to reach a decision regarding risk reduction (NAS, 1983:3). This thesis is focused on introducing and evaluating risk assessment/RBCA methods applicable to DoD decision-makers in the ROK, and as such, risk management will not be addressed in detail. Although various risk assessment/RBCA methods have been proposed (e.g. Masters (1998); National Academy of Sciences (1983)), this literature review is based upon the methodology proposed by the EPA for use in baseline risk assessments at Superfund sites. The EPA Superfund methodology was selected since it served as the predecessor for many of the Risk-Based Corrective Action (RBCA) approaches currently in use and it best depicts the core activities that will be necessary to perform risk assessments at DoD installations in the ROK.

The four primary elements comprising a risk assessment as defined by the EPA for Superfund site baseline risk assessments include 1) data collection and analysis, 2) exposure assessment, 3) toxicity assessment, and 4) risk characterization. The risk assessment framework is illustrated in Figure 4.

Data Collection and Analysis. Data collection and analysis entails gathering and analyzing the site data relevant to the human health evaluation and identifying the substances present at the site that are the focus of the risk assessment process (EPA RAG, 1989:1-6). These data are obtained through the ASC process and incorporation of on-site analytical methods. Data collection and analysis may result in elimination of chemicals of potential concern from the list of those initially identified, by

comparing actually measured concentrations with background levels or toxicity levels (Hunter, 1995:9). Note that data requirements of the risk assessment method must be considered in the development of the dynamic workplan.
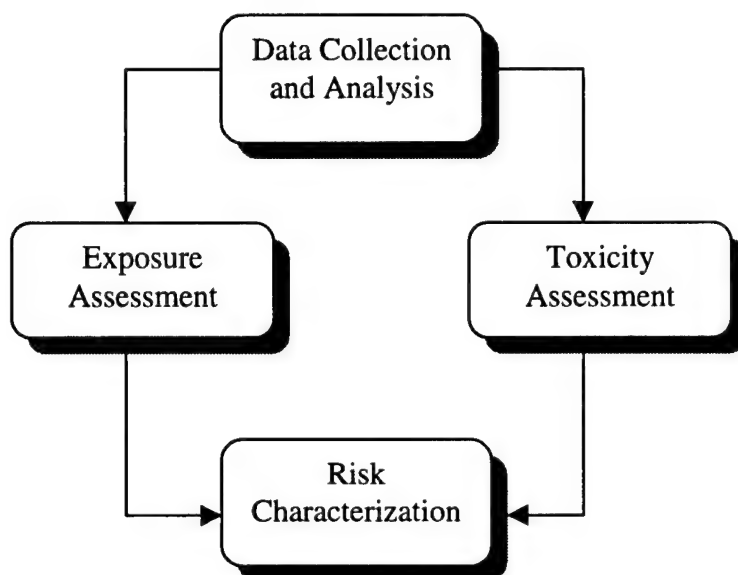
Figure 4. Framework for the Baseline Risk Assessment (EPA, 1989:1-7)

Exposure Assessment. The exposure assessment process begins after the chemical data have been collected and validated and the chemicals of potential concern have been identified (Hunter, 1995:9). An exposure assessment is conducted to estimate the magnitude of actual and/or potential human exposures, and the pathways by which humans may be exposed (EPA RAG, 1989:1-6). In the exposure assessment, reasonable maximum exposure (RME) estimates are developed for both current and future land use assumptions. RME estimates are subjective estimates of the maximum exposure the receptor in question could receive over each pathway under study, keeping in mind that this receptor likely would not receive maximum exposure through all pathways (Hunter, 1995:10). Current exposure estimates are used to determine whether a threat exists based

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on existing exposure conditions at the site, while future exposure estimates are used to

provide decision-makers with an understanding of potential future threats and include a

qualitative estimate of the likelihood of such exposures occurring (EPA RAG, 1989:1-6).

DoD decision-makers can decide if both current and future exposure assessments are

required, and if so, what potential future site uses may be considered. A schematic of the

exposure assessment process is illustrated in Figure 5.

STEP 1

Characterize Exposure Setting

- Physical Environment
- Potentially Exposed Populations

STEP 2

Identify Exposure Pathways

- Chemical Source/Release
- Exposure Point
- Exposure Route

STEP 3

Quantify Exposure

Exposure Concentration   Intake Variables

Pathway-Specific Exposure
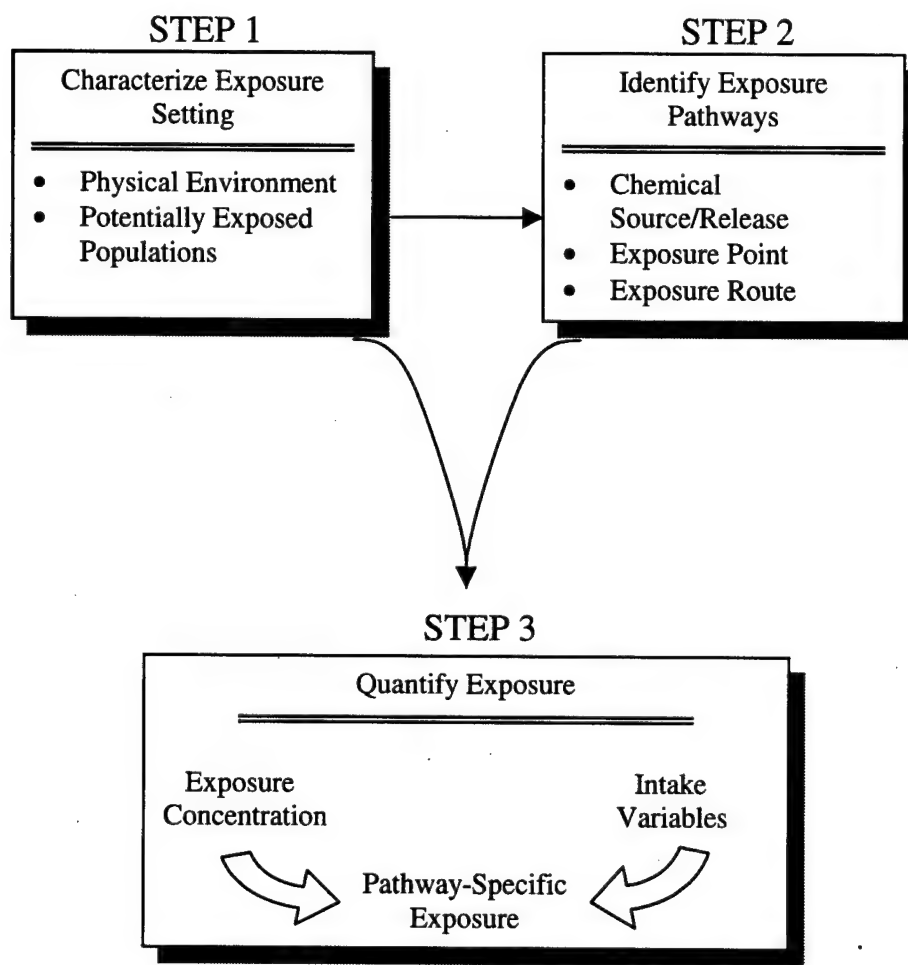
Figure 5. The Exposure Assessment Process (EPA RAG, 1989:6-3)

As depicted in Figure 5, the exposure assessment proceeds with the following

three steps: 1) characterization of exposure setting; 2) identification of exposure

pathways; and 3) quantification of exposure (Hunter, 1995:12). In the initial step, characterization of the exposure setting with respect to the general physical characteristics of the site and the characteristics of the populations on and near the site is accomplished. Basic site characteristics such as climate, vegetation, groundwater hydrology, and the presence and location of surface water are identified in this step (EPA RAG, 1989:6-2). Populations also are identified and are described with respect to those characteristics that influence exposure, such as location relative to the site, activity patterns, and the presence of sensitive sub-populations (EPA RAG, 1989:6-2). Sensitive sub-populations may be children or the elderly who may be at increased risk from chemical exposures due to increased sensitivity, behavior patterns that may result in high exposure, and/or current or past exposures from other sources (Hunter, 1995:12).

The second step in the exposure assessment process involves identification of those pathways by which the previously-identified populations may be exposed (EPA RAG, 1989:6-4). Each exposure pathway describes a unique mechanism by which a population may be exposed to the

chemicals at the site or originating from the site. A pathway is considered complete if the following exist: 1) a source or chemical release from a source; 2) an exposure point where contact can occur; and 3) an exposure route by which contact can occur (EPA RAG:6-17). After exposure points are determined, probable exposure routes (e.g. ingestion, dermal contact) are identified based on the media contaminated and the anticipated activities at the exposure points (Hunter, 1995:13).

The final step in the exposure assessment process involves quantifying the magnitude, frequency, and duration of exposure for the populations and exposure

pathways selected for quantitative evaluation (Hunter, 1995:13). This step is most often conducted in two stages: first, exposure concentrations are estimated, followed by quantification of pathway-specific intakes. The three categories of variables used to estimate pathway-specific intakes include chemical-related variables (e.g. exposure concentrations), variables that describe the exposed populations (e.g. contact rate, exposure frequency, exposure duration, and body weight), and assessment-determined variables (e.g. averaging time) (EPA RAG, 1989:6-19).

Conducting an exposure assessment involves the following: analyzing contaminant releases; identifying exposed populations and all potential pathways of exposure; estimating exposure point concentrations for specific pathways (based on both environmental monitoring data and predictive chemical modeling results); and estimating contaminant intakes for specific pathways (Hunter, 1995:10). The results of this assessment are pathway-specific intakes for current and future exposures to individual substances. Some of the common chemical release sources are listed in Table 8.

The overall objective of the exposure assessment is to estimate the type and magnitude of exposures to chemicals of potential concern that are present at or migrating from a site (EPA RAG, 1989:6-1). The results of the exposure assessment are combined with chemical-specific toxicity information in order to characterize the potential risks.

Table 8. Common Chemical Release Sources at Sites in the Absence of Remedial Action (EPA RAG, 1989:6-10)

Receiving Medium	Release Mechanism	Release Source
Air	Volatilization	Surface wastes—lagoons, ponds, pits, spills Contaminated surface water Contaminated surface soil Contaminated wetlands Leaking drums
	Fugitive dust generation	Contaminated surface soil Waste piles
Surface water	Surface runoff	Contaminated surface soil
	Episodic overland flow	Lagoon overflow Spills, leaking containers
	Groundwater seepage	Contaminated groundwater
Groundwater	Leaching	Surface or buried wastes Contaminated soil
Soil	Leaching	Surface or buried wastes
	Surface runoff	Contaminated surface soil
	Episodic overland flow	Lagoon overflow Spills, leaking containers
	Fugitive dust generation/deposition	Contaminated surface soils Waste piles
	Tracking	Contaminated surface soil
Sediment	Surface runoff, episodic overland flow	Surface wastes—lagoons, ponds, pits, spills Contaminated surface soil
	Groundwater seepage	Contaminated groundwater
	Leaching	Surface or buried wastes Contaminated soil
Biota	Uptake (direct contact, ingestion, inhalation)	Contaminated soil, surface water, sediment, groundwater or air Other biota

Toxicity Assessment. The toxicity assessment phase of the risk assessment considers the following: 1) the types of adverse health effects associated with chemical exposures; 2) the relationship between magnitude of exposure and adverse effects; and 3) related uncertainties such as the weight of evidence of a particular chemical's carcinogenicity in humans (EPA RAG, 1989:1-6). The purpose of the toxicity assessment is to weigh available evidence regarding the potential for particular contaminants to cause adverse effects in exposed individuals and to provide, where possible, an estimate of the relationship between the extent of exposure to a contaminant and the increased likelihood and/or severity of adverse effects. The primary steps in the toxicity assessment are illustrated in Figure 6.

Toxicity assessments for contaminants found at hazardous waste sites are generally accomplished in two steps, hazard identification and dose-response assessment (EPA RAG, 1989:1-6). Hazard identification is the process of determining whether or not a particular chemical is causally linked to particular health effects, such as cancer or birth defects (Masters, 1998:123). Hazard identification also involves characterizing the nature and strength of the evidence of causation. As an example, the EPA weight of evidence classification system for carcinogenicity is shown in Table 9. Dose-response assessment is the process of characterizing the relationship between the dose of an agent administered or received and the incidence of an adverse health effect (Masters, 1998:123).

```
┌─────────────────────────────────────────┐
│ Step 1: Gather Toxicity Information--     │
│         Qualitative and Quantitative--    │
│         For Substances being Evaluated    │
└─────────────────────────────────────────┘
                    ⇩
┌─────────────────────────────────────────┐
│ Step 2: Identify Exposure Periods for     │
│         which Toxicity Values are         │
│         Necessary                         │
└─────────────────────────────────────────┘
                    ⇩
┌─────────────────────────────────────────┐
│ Step 3: Determine Toxicity Values for     │
│         Non-carcinogenic Effects          │
└─────────────────────────────────────────┘
                    ⇩
┌─────────────────────────────────────────┐
│ Step 4: Determine Toxicity Values for     │
│         Carcinogenic Effects              │
└─────────────────────────────────────────┘
                    ⇩
┌─────────────────────────────────────────┐
│ Step 5: Summarize Toxicity Information    │
└─────────────────────────────────────────┘
```
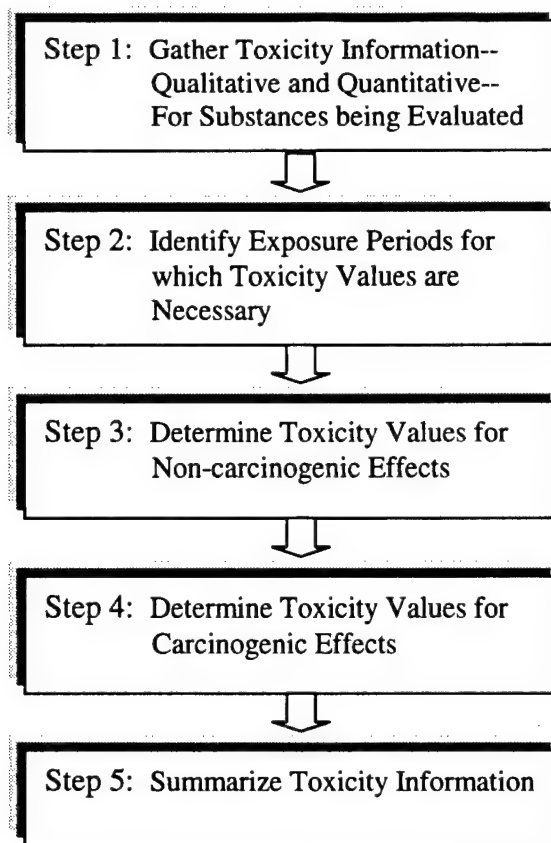
Figure 6. Steps in Toxicity Assessment (EPA RAG, 1989:7-4)

Many different dose-response relationships are possible for any given agent depending upon such conditions as whether the response is carcinogenic or non-carcinogenic and whether the experiment is a one-time acute test or a long-term chronic test (Masters, 1998:123).

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Table 9. EPA Weight-of-Evidence Classification System for Carcinogenicity
(EPA RAG, 1989:7-11)

Group	Description
A	Human carcinogen
B1 or B2	Probable human carcinogen B1 indicates that limited human data are available B2 indicates sufficient evidence in animals and inadequate or no evidence in humans
C	Possible human carcinogen
D	Not classifiable as to human carcinogenicity
E	Evidence of non-carcinogenicity for humans

From the quantitative dose-response relationship, toxicity values (e.g. reference doses and slope factors) are derived that can be used to estimate the incidence or potential for adverse health effects as a function of human exposure to the agent (Hunter, 1995:15). These toxicity values are then used in the risk characterization step to estimate the likelihood of adverse effects occurring in humans at different exposure levels (Hunter, 1995:15). The EPA's Integrated Risk Information System (IRIS) and Health Effects Assessment Summary Tables (HEAST) are the databases containing the toxicity data and information commonly used in site risk assessments (EPA RAG, 1989:7-13).

Risk Characterization. The final step in the risk assessment process, risk characterization, summarizes and combines outputs of the exposure assessments (e.g. intakes for all exposure pathways and land uses and for all relevant substances) and the toxicity assessment (e.g. toxicity values for all exposure routes and relevant substances) to characterize site risk, both in quantitative expressions and qualitative statements (Hunter, 1995:15). In order to characterize potential non-carcinogenic effects, comparisons are made between projected intakes of substances and toxicity values; this

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value is known as the reference dose (EPA RAG, 1989:8-1). The reference dose (RfD) is obtained by dividing the no-observed-adverse-effects-level (a dose threshold at which no adverse effects are seen) by an uncertainty factor (a basic factor of safety or accommodation of uncertainty). The units of the RfD are in mg/kg-day, averaged over a human lifetime (default is commonly 70 years). In order to characterize potential carcinogenic effects, probabilities that an individual will develop cancer over a lifetime of exposure are estimated from projected intakes and chemical-specific, dose-response information; this value is known as the slope factor (EPA RAG, 1989:8-1). The slope factor is obtained by dividing the incremental lifetime cancer risk (caused by the particular chemical) by the chronic daily intake (mg/kg-day), and is expressed in units of $(mg/kg-day)^{-1}$. The slope factor is the slope of the dose-response curve at a particular intake amount.

Projected intakes are determined using measured contaminant exposure levels or levels predicted through fate and transport modeling (EPA RAG, 1989:1-6). Major assumptions, scientific judgements, and to the extent possible, estimates of the uncertainties embodied in the assessment are also presented as part of the risk characterization process (EPA RAG, 1989:8-1).

Risk-Based Corrective Action. Amid the widespread recognition of flaws in U.S. environmental cleanup regulations, RBCA guidelines have evolved for hazardous waste sites. Rather than aiming for a uniform goal of reducing site contaminants to natural or background levels or achieving maximum cleanup possible with current technology, the RBCA framework assesses current and potential future risks at a site and sets cleanup goals accordingly (Begley, 1996:438A). RBCA addresses the question of

how clean is clean by matching the urgency and extent of remediation with the risk to human health, safety and the environment (Begley, 1996:438A).

By the early 1990's, remedial experience demonstrated the following distinctive trends (Koch, 1996:40):

1. Most site cleanup goals were "one-size-fits-all" concentration standards. Few were predicated on no risk or zero degradation, nor did they estimate risks unique to each site;

2. Risks at a specific site were mitigated, but often risks were moved to landfills or shifted from groundwater to the air;

3. The time needed to achieve cleanup standards usually exceeded original design predictions;

4. Total removal of contaminants "locked-up" in some soils, even by aggressive in-situ techniques, did not occur;

5. Treatment costs later in the remediation process were disproportionate to mass removal in achieving statutory thresholds; and

6. Removal of these small amounts of residual contaminants (at great cost) did not necessarily correspond to a significant reduction of public risk.

In order to address these trends, the concept of RBCA was developed. RBCA's flexible approach focuses efforts and dollars on sites needing attention and speeds the evaluation and corrective response while protecting public health and environmental resources.

The real value of RBCA lies in its potential to help regulatory agencies and responsible parties oversee/manage cleanup of hazardous waste sites (OSWER Dir, 1996). In addition, RBCA can provide a coherent decision-making framework to help

keep transaction costs under control. Thus, while RBCA can be as protective of human health and the environment as other approaches, it offers a scientifically sound and administratively effective way to respond to the pressures for timely action at a large numbers of sites while efficiently using resources (OSWER Dir, 1996). Based upon these characteristics, RBCA would seem to be an ideal approach for use by DoD decision-makers in the ROK to address hazardous waste sites located there. Located at Appendix 2 is a broad outline of how RBCA could be applied to determine an appropriate TPH standard.

Specific Risk Assessment Methods. The selection of specific risk assessment/corrective action methods that will be evaluated for application at DoD installations in the ROK includes the ASTM RBCA method, the DoD Relative Risk Site Evaluation method, and the state of Hawaii RBCA method. This list is not all-inclusive, however, it contains three pertinent approaches that are directly applicable to DoD installations in the ROK. Note that the DoD Relative Risk Site Evaluation method provides a relative risk ranking (high, medium, or low), while the two RBCA methods provide remedial goals. Both RBCA methods assume acceptable risks (commonly 10^{-6}) in the initial phase of the process and allow the user or decision-maker to evaluate and propose acceptable risk levels in subsequent phases. Acceptable risk is that risk (of harm or disease, such as cancer) attributed to the contaminant(s) of concern, which is over and above any background risk that may exist. Thus, the RBCA methods are focused on providing risk-based remedial action levels or goals.

ASTM RBCA Method. The ASTM RBCA method uses a tiered approach that integrates site assessment and response actions with human health risk

assessment to determine the need for remedial action and to tailor corrective action activities to site-specific conditions and risks (ASTM PS-104, 1998:1). The evaluations and methods used begin with simple analyses in Tier 1, and move to more complex evaluations in Tier 2 and Tier 3. The process of gathering and evaluating data is conducted in a scaled fashion, thus only those data that are necessary for that tier's decision-making are collected at each tier.

Policy. The ASTM RBCA method is intended to help direct and streamline the corrective action process and to complement but not supersede governing regulations, policies, and directives. The method can be used where there may not be a regulatory framework for corrective action (such as at DoD sites in the ROK), where the user wishes to conduct corrective action under a voluntary cleanup program, or under Brownfields initiatives (ASTM PS 104, 1998:1). In addition, it can be used as an over-arching framework when several different agency programs affect the site.

The ASTM RBCA process does not provide a relative risk site evaluation or similar relative ranking. The RBCA process is implemented in a tiered approach, involving increasingly sophisticated levels of data collection and analysis as the user proceeds through the tiers (ASTM PS 104, 1998:7). Thus, following the ASTM RBCA method provides, in most cases, a detailed, chemical-specific risk assessment. With the data obtained, the user could, if desired or required, perform a relative risk assessment.

Inputs. Numerous technical policy decisions must be made prior to implementing the RBCA process, including defining DQOs, determining target risk levels, and addressing resource protection (ASTM PS 104, 1998:2). Data

requirements depend upon the extent of tiered evaluation decided upon by decision-makers.

A Tier 1 evaluation is a risk-based analysis utilizing non-site-specific values for complete and potentially complete direct and indirect human exposure pathways. The non-site-specific values developed for human exposure pathways are based on conservative exposure factors and fate and transport parameters and methods to estimate potential exposures by means of potential exposure pathways and various land use categories (ASTM PS 104, 1998:6). A Tier 2 evaluation is a risk-based analysis for human exposure pathways comparing statistically representative site characterization data to Tier 1 values, applying the direct exposure values established under a Tier 1 evaluation at the point(s) of exposure developed for a specific site, or development of values for potential indirect exposure pathways at the point(s) of exposure using site-specific conditions and the Tier 1 methodology (ASTM PS 104, 1998:6). A Tier 3 evaluation is a risk-based analysis for human exposure pathways using advanced exposure assessment, toxicity and risk assessment techniques allowing maximum flexibility to develop site-specific values for potential direct and indirect exposure pathways at the point(s) of exposure based on site-specific conditions (ASTM PS 104, 1998:6).

In determining the data required to utilize this method, a basic outline of the method is crucial. The following general sequence of events is prescribed by RBCA, Tier 1 (ASTM PS 104, 1998:2):

1. Define data requirements and develop DQOs and perform initial site assessment and develop the first iteration of the conceptual model;

2. Classify the site by the urgency of initial response;

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3. Implement the initial response action appropriate for the site based on the selected site classification;

4. Compare concentrations of chemical(s) of concern at the site with human health Tier 1 Risk Based Screening Levels (RBSLs) for complete and potentially complete exposure pathways. RBSLs are defined as non-site-specific human health RBCA target levels for chemical(s) of concern utilized during the Tier 1 evaluation. Determination of RBSLs requires application of numerous pathway and chemical-specific exposure equations and associated media-specific parameters applicable to the site;

5. If concentrations of chemical(s) of concern are below the RBSL for all complete and potentially complete exposure pathways, then no further action is warranted;

6. If concentrations of chemical(s) of concern are above the RBSL, then one or more of the following is appropriate – further tier evaluation, implementation of interim remedial action, application of RBSLs as remedial action target levels.

The following general sequence of events is prescribed by RBCA, Tier 2 (ASTM PS 104, 1998:2-3):

1. Define Tier 2 data requirements, DQOs, and collect addition site-specific information and update the site conceptual model, as necessary;

2. Develop Site Specific Target Levels (SSTLs) and points of compliance for complete and potentially complete exposure pathways. SSTLs have the same definition as RBSLs, yet are applicable to Tier 2 and Tier 3 evaluations. Their calculations are

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similar, however, with more detailed contaminant, media, pathway and receptor data. Also they tend to be much more precise in assessing risk;

3. Compare concentrations of chemical(s) of concern at the site with Tier 2 evaluation SSTL at the determined point(s) of compliance or source area(s);

4. If concentrations of chemical(s) of concern are below the SSTL for all complete and potentially complete exposure pathways, then no further action is warranted;

5. If concentrations of chemical(s) of concern are above the SSTL, then one or more of the following actions is appropriate – further tier evaluation, implementation of interim remedial action to change the site classification and facilitate reassessment of the tier evaluation, and/or application of SSTLs as remedial action target levels.

The following general sequence of events is prescribed by RBCA, Tier 3 (ASTM PS 104, 1998:3):

1. Define Tier 3 data requirements, DQOs and collect additional site-specific information and update the site conceptual model, as necessary;

2. Develop SSTL and point(s) of compliance;

3. Compare the concentrations of chemical(s) of concern at the site with the Tier 3 evaluation SSTL at the determined point(s) of compliance or source area(s);

4. If concentrations of chemical(s) of concern are below the SSTL for all complete and potentially complete exposure pathways, then no further action is warranted;

5. If concentrations of chemical(s) of concern are above the SSTL, then one or more of the following actions is appropriate – implementation of interim remedial action

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to change the site classification and facilitate reassessment of the tier evaluation and/or application of SSTLs as remedial action target levels.

Data inputs are directly tied to the particular tier specified as adequate by the decision-maker. Much of the data required for the ASTM RBCA method is similar (again, depending on the tier) to the CERCLA Baseline Risk Assessment, with the primary difference being how the data is used in selection of corrective action. Basic requirements include the following: developing DQOs, performing an initial site assessment (determining contaminant concentrations and contaminant distributions, sources and source areas of contaminants, human receptors, transport and exposure pathways, current and future site use, regional geologic/hydrogeologic characteristics, and points of compliance), developing a conceptual site model (selecting contaminant(s) of concern, calculating RSBLs/SSTLs, selecting applicable pathways and receptors), comparing concentrations of contaminant(s) of concern with RSBLs/SSTLs, and determining what are acceptable concentrations for contaminants of concern for the particular site and assessed risk (ASTM PS 104, 1998:11). The ASTM RBCA methodology is shown in Figure 7.

Output. Through application of the ASTM RBCA method, a wealth of data and information concerning the site will be available, of course, depending upon the particular tier specified as adequate by the decision-maker. After completion of the tier analyses, a RBCA report will be prepared. The report must include all of the data collected to support the RBCA decisions that were made by the decision-maker. The report content will depend on the specific site, the tier evaluation and the requirements of the environmental executive agent/governing agency, however, in broad

summary, the report should typically include the following: a site description; a summary of site ownership and use; a summary of past releases and potential source areas; a summary of current and completed site activities; a description of hydrogeologic conditions; a summary and discussion of the site conceptual model and the exposure pathway analysis; a summary of tier evaluations conducted, including the methods and assumptions used to derive the RBSLs/SSTLs; a summary of the analytical data and the appropriate RBSLs/SSTLs used; site plan, contaminant concentration maps for chemical(s) of concern, and any other desired maps/plans; and, a summary of the technical policy decisions (ASTM PS 104, 1998:19-20).

Initial Site Assessment
Conduct site investigation and summarize available site information

Interim Remedial Action
Conduct partial source removal or other actions to reduce the risk(s) and to reclassify the site, then return to the applicable Tier Evaluation

Site Classification for Initial Response
Classify site based on the need for initial response actions. Implement initial response actions. Reclassify site as appropriate and collect additional data as necessary.

Tier 1 Evaluation
Identify reasonable potential sources, transport pathways, receptors, and exposure pathways. Select appropriate Tier 1 RBSL and compare site conditions to RBSL.

Site conditions above screening criteria? — No / Yes

Remediation to RBSL practicable? — No / Yes

Interim remedial action appropriate? — Yes / No

Tier 2 Evaluation
Collect additional data as needed. Review and revise site conceptual model, as appropriate. Develop Tier 2 SSTLs and compare site conditions to SSTLs.

Site conditions above Tier 2 SSTL? — No / Yes

Remediation based on Tier 2 SSTL practicable? — No / Yes

Interim remedial action appropriate? — Yes / No

Tier 3 Evaluation
Collect additional site data as needed.

Site conditions above Tier 3 SSTL? — No / Yes

Interim remedial action appropriate? — Yes / No

Return to tier site evaluation, if conditions have changed? — Yes / No

Remedial Action Program
Identify alternatives based on target levels, including combinations of remediation, natural attenuation, and institutional controls. Implement the preferred alternative.

Continued monitoring required? — Yes / No

Monitoring
Monitoring program confirms that corrective action goals are satisfied — Yes

No Further Action

Figure 7. ASTM RBCA Flowchart (ASTM PS 104, 1998:9)

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DoD Relative Risk Evaluation Method. The DoD Relative Risk method is a qualitative and easy to understand methodology for evaluating relative risks posed by the broad range of sites that exist at DoD installations and the broad range of data available (Rowe and Turkeltaub, 1996:48). The method is a tool to assist in sequencing environmental restoration work. It is a means of grouping sites into high, medium, and low risk categories based on an evaluation of site information using the contaminant hazard factor (CHF), the migration pathway factor (MPF), and the receptor factor (RF) (Rowe and Turkeltaub, 1996:49).

Policy. The DoD relative Risk Site Evaluation Method is the procedure developed and employed by the DoD at CONUS installations. This method is a product of the Interservice Relative Risk Working Group, which developed it in response to Deputy Undersecretary of Defense (DUSD), Environmental Security (ES) Management Guidance for Execution of the FY94/95 and Development of the FY96 Defense Environmental Restoration Program (RRSEP, 1997). The method is a procedure used by all DoD Components within CONUS to evaluate the relative risk posed by a site in relation to other sites.

Inputs. Required inputs for the DoD Relative Risk method include both qualitative and quantitative information. The framework uses three principal factors: 1) the CHF, 2) the MPF, and 3) the RF. Factors are based on a quantitative evaluation of CERCLA hazardous substances, pollutants, or contaminants, as well as a qualitative evaluation of pathways and human and ecological receptors (although ecological risk assessment will not be addressed in this thesis) in the four

media most likely to receive significant exposure – groundwater, surface water, sediment, and surface soils (Rowe and Turkeltaub, 1996:49).

The CHF is based on the ratio of the maximum concentration of a contaminant reliably detected in a medium to a risk-based comparison value (RBCV) for the contaminant in that medium (Rowe and Turkeltaub, 1996:49). The RBCVs are found in Appendix B of the DoD Relative Risk Site Evaluation Primer.

Information about the migration pathways of contamination for a site is summarized as the MPF. MPFs are determined by matching available site information on pathways with definitions (found in the Primer) about the likelihood of contaminant migration away from the original contaminant source toward a point of exposure (Rowe and Turkeltaub, 1996:49). Individuals or groups performing the relative risk site evaluations determine the MPF on the basis of professional judgement and consideration of available site information.

Information about the present or future likelihood of receptors for each site is summarized as the RFs are determined by matching available information on receptors at sites with a set of definitions (identified in the Primer) applicable to the various media at the site (Rowe and Turkeltaub, 1996:50). RF determinations are made on the basis of available information and professional judgements about the site.

Output. The overall output of the DoD relative Risk Site Evaluation Method is a site ranking of high, medium, or low. Specific outputs from each of the three factors for each pathway are combined using a relative risk site evaluation matrix (found in the Primer) to obtain the relative risk for each medium. This process is illustrated in Figure 8.

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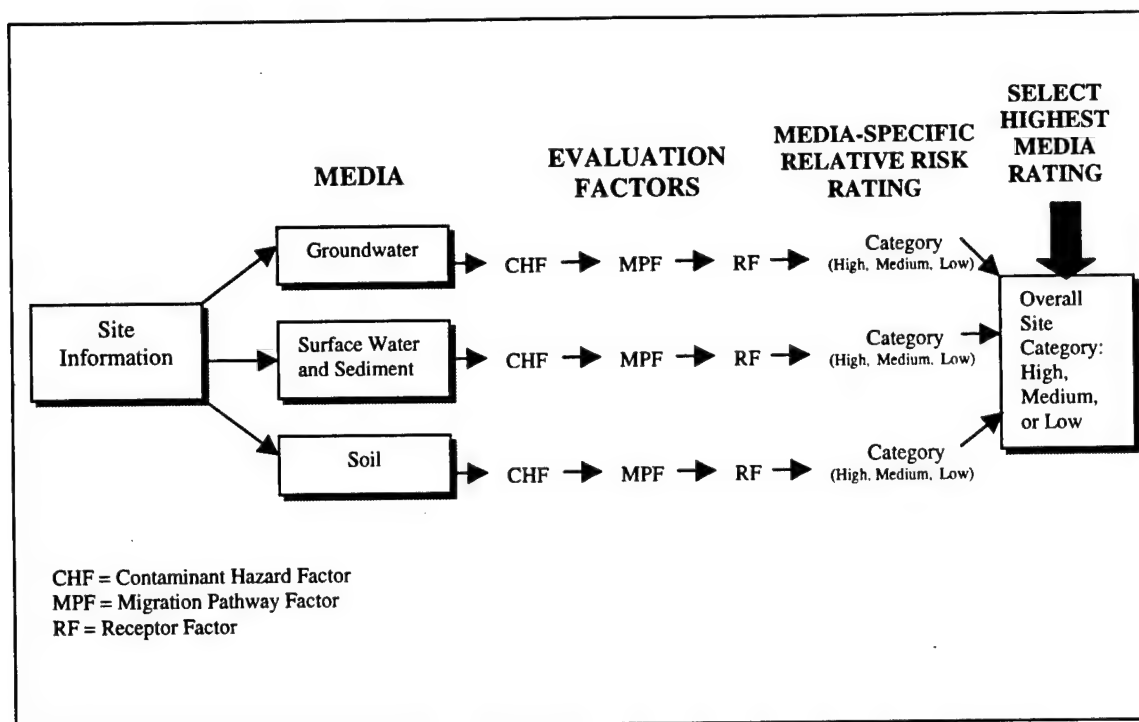
Figure 8. Flow Diagram of the Relative Risk Site Evaluation Framework
(DoD Primer, 1997).

The CHF can be either significant (sum of CHFs or individual CHF, if only a single contaminant, greater than 100), moderate (greater than or equal to 2 but less than 100), or minimal (less than 2) (Rowe and Turkeltaub, 1996:49). MPFs of evident, potential, or minimal are determined by comparison of input data and information with definitions outlined in the Primer. Likewise, RFs of identified, potential, or limited are determined by comparison of input data and information with definitions outlined in the Primer.

Once media-specific relative risks (high, medium, or low) have been determined, the highest ranked medium relative risk is chosen as the relative risk designation for the entire site. This process is illustrated in Figure 9.

CHF = SIGNIFICANT

	Identified	Potential	Limited
Evident	H	H	M
Potential	H	H	M
Confined	M	M	L

MPF (vertical axis) RF (horizontal axis)

CHF = MODERATE

	Identified	Potential	Limited
Evident	H	H	M
Potential	H	M	L
Confined	L	L	L

MPF (vertical axis) RF (horizontal axis)

CHF = MINIMAL

	Identified	Potential	Limited
Evident	H	M	L
Potential	M	L	L
Confined	L	L	L

MPF (vertical axis) RF (horizontal axis)

CHF = Contaminant Hazard Factor
MPF = Migration Pathway Factor
RF = Receptor Factor
H   = High
M   = Medium
L   = Low

* If sampling results for a particular medium are below detection limits or are detected within established background concentration ranges, then the medium should automatically be assigned a rating of *Low*.

Figure 9. Relative Risk Site Evaluation Matrix (Primer, 1997)

State of Hawaii RBCA Method. The state of Hawaii offers

responsible parties three options (tiers) in order to establish remedial goals for

contaminated soil and groundwater that are protective of human health and the

environment. In Tier 1, a facility refers to conservative, default ("generic") soil action

levels (SALs) and groundwater criteria (if groundwater is impacted) established by the

Hawaii Department of Health (HDOH) that can be used at any impacted site; Tier 2

permits a facility to substitute actual site data into the same Tier 1 models and evaluate

groundwater protection and direct exposure concerns on a limited, but more site-specific

basis; Tier 3 permits a facility to employ alternative groundwater impact models, direct-

exposure models, and/or input parameter assumptions to evaluate an impacted site,

supporting all input data with a thorough risk assessment (HDOH VOL1, 1996:3).

HDOH (the state environmental executive agent) groundwater

criteria were based on state and federal standards for drinking water and surface water,

while SALs were developed to meet two major goals: 1) ensure that residual

contamination in the vadose zone media (soil, sediment, rock, etc.) does not create an

unacceptable health risk for direct human exposure through inhalation, ingestion, and

dermal contact, and 2) ensure that leaching of residual contamination from the vadose

zone does not lead to a negative impact on groundwater resources or on surface waters

(HDOH VOL1, 1996:2).

Policy. This method is a refined RBCA process that has

been implemented by the HDOH for assessment and remediation of sites with

contaminated soil and groundwater. Like the ASTM RBCA method, this method can be

used where there may not be a regulatory framework for corrective action and where the

user or responsible party wishes to conduct a corrective action. This tiered approach allows users to choose between default, risk-based SALs and more detailed, site- and pathway-specific, risk-based SALs (HDOH VOL1, 1996:2).

The HDOH RBCA method does not provide a relative risk site evaluation or similar relative ranking. Similar to the ASTM RBCA method, the HDOH RBCA is implemented in a tiered manner, involving increasingly sophisticated levels of data collection and analysis as the user proceeds through the tiers. The decision-maker decides which tier to utilize (with some situations automatically requiring a specific tier). With data obtained from this method, the user could, if desired or required, perform a relative risk assessment.

Inputs. Inputs required in the utilization of the HDOH RBCA method are directly tied to the tier selected to determine site soil and groundwater action levels. The inputs range from contaminant concentrations and aquifer characteristics to selection of HDOH-approved computer models and levels of acceptable risk, again depending upon the tier of evaluation chosen by the decision-maker (or required due to specific site conditions identified by HDOH).

Tier 1 action levels applicable to a given site are determined with respect to two site characteristics: 1) utility (drinking water or non-drinking water) of groundwater impacted or potentially impacted, and 2) annual rainfall at the site (less than or greater than 200 cm/yr) (HDOH VOL1, 1996:1). Along with determining the above data, identification and "quantitation" of chemicals of concern, and determination of the areal extent and location of contamination is required. Depending upon which category the site falls into as far as the above-listed two

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characteristics, SALs and groundwater criteria are prescribed. Groundwater criteria are based on state and federal acute or, when available, chronic surface water standards (HDOH VOL1, 1996:3). Site characterization efforts must determine if groundwater is impacted or potentially impacted. In generating the SALs, exposure pathways to soil (inhalation, ingestion, and dermal adsorption) are assumed complete (HDOH VOL1, 1996:4). Table 10 identifies a sample of HDOH RBCA Tier 1 SALs and groundwater criteria.

Table 10. Tier 1 Soil Action Levels and Groundwater Criteria
(HDOH VOL1, 1996:11-12)

| Contaminant | Rainfall ≤ 200 cm/year | | | | Rainfall ≥ 200 cm/yr | | | |
| | Drinking water source threatened | | Drinking water source not threatened | | Drinking water source threatened | | Drinking water source not threatened | |
	Ground-water (mg/L)	Soil (mg/kg)	Ground-water (mg/L)	Soil (mg/kg)	Ground-water (mg/L)	Soil (mg/kg)	Ground-water (mg/L)	Soil (mg/kg)
Benzene	0.005	0.05	1.7	0.68	0.005	0.05	1.7	1.7
Toluene	1.0	16	2.1	5.5	1.0	16	2.1	34
Ethylbenzene	(0.014)	0.50	0.14	0.13	(0.14)	0.50	0.14	0.50
Xylene	10	23	[10]	8	10	23	[10]	23
Benzo(a)pyrene	0.0002	1.0de	[0.0002]	1.0de	0.0002	1.0de	[0.0002]	1.0de

Notes: ( ) indicates same as surface water standard; surface water standard more stringent than drinking water standard.
[ ] indicates same as drinking water; surface water standard not set.
de indicates direct exposure concerns dominate

Tier 1 SALs are set to satisfy groundwater and direct exposure objectives at sites with extensive amounts of contamination, but for those sites with limited contamination, site-specific Tier 2 SALs may be more applicable. The Tier 2 process allows facilities to take into account the actual volume of contaminated soil at the site, the depth to groundwater and the expected dilution of contaminant leachate as it passes into groundwater (HDOH VOL1, 1996:17). Corresponding site-specific data that may be

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incorporated into the Tier 2 models include those required for the Tier 1 analysis plus identification of aquifer characteristics, such as regional groundwater gradient and soil chemical and hydraulic properties, and the physical and chemical properties of the chemical(s) of concern.

Tier 2 SALs can be generated by use of one or more of four HDOH-approved computer models and spreadsheets, including SESOIL, QUICKSOIL, DAF (dilution attenuation factor), and DETIER2. In this tier, the user inputs site-specific data into the applicable models to generate risk-based SALs that are more appropriate for the specific site. Input information includes model simulation information, climate data, soil property data, contaminant physio-chemical constants, application data, soil column properties, and pollutant loading data (HDOH VOL1, 1996:22-27). Final, contaminant-specific SALs for a site are determined by comparing the results of the groundwater impact models and direct-exposure models and selecting the SAL that corresponds to the impact of most concern (i.e., the most stringent action level) for the site (HDOH VOL1, 1996:29).

Tier 3 risk assessments may include some combination of alternative vadose-zone fate-and-transport models, direct-exposure models, and exposure pathway evaluations as well as more complex groundwater fate-and-transport models chosen by the user (HDOH VOL1, 1996:31). In the Tier 3 RBCA framework, the facility is permitted to propose alternative, acceptable levels of risk at the site. If the facility cannot meet the target acceptable risk level of 10^{-6} but can demonstrate the ability to meet the EPA-designated acceptable risk range of 10^{-4} to 10^{-6}, then various factors such as economics, technical

feasibility, etc., will be considered by HDOH in determining final appropriate risk levels and corresponding SALs (HDOH VOL1, 1996:31).

Output. Due to the fact that this is a corrective action-focused method, output is not a relative risk ranking or an attributable level of risk. For Tier 1 and Tier 2 analysis, an attributable level of risk of 10^{-6} is assumed in determining SALs, while in Tier 3, an alternative attributable level of risk (10^{-4} to 10^{-6}) may be proposed. Instead, the HDOH RBCA method generates target levels for which to remediate chemical(s) of concern based upon contaminant type(s), aquifer characteristics, available receptors, and completed pathways.

Specifically, in performing a Tier 1 analysis, the decision-maker would have the following information: utility of groundwater impacted or potentially impacted, climatology data, and site characterization information, including (at a minimum) identification and "quantitation" of chemical(s) of concern and determination of the areal extent and location (within the aquifer) of contamination. Using this information and data, the decision-maker would then have default SALs and groundwater action levels providing a conservative remedial action goal.

For a Tier 2 analysis, outputs would include those from a Tier 1 analysis, plus more detailed aquifer characteristics such as regional groundwater gradient, soil chemical and hydraulic properties, and contaminant properties. In addition, through the process of "running" HDOH-approved exposure models, SALs generated are much more specific to the site, potential receptors, and completed pathways. Default groundwater action levels still apply.

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For a Tier 3 analysis, the output information from Tier 1 and Tier 2 would be available as well as the following (as applicable): detailed contaminant fate and transport data, detailed direct-exposure model data and/or an in-depth exposure pathway model information, and a decision-maker proposed level of attributable risk based upon the compilation of data. The resulting SALs would more accurately reflect attributable risk, while being strongly supported with a thorough, decision-maker performed risk assessment. Default groundwater and action levels still apply.

E. Multiple Criteria Decision-Making

Given that the accelerated site characterization process and the associated innovative technologies and RBCA methods presented represent feasible ways of accomplishing decision-maker objectives, a technique is needed to discover what alternatives best meet decision-maker needs. Such techniques lie in the realm of multiple criteria decision-making (MCDM).

The ability to make rational decisions is one of mankind's unique attributes, and man has continuously devised ways and means to enlarge his abilities to cope with the growing complexity of his decision problems. A characteristic of most of the formal techniques that have been used for decision-making is the selection of the best alternative with respect to a certain figure of merit. However, the nature of many decision problems has changed considerably in recent years and serious doubts have been raised as to the adequacy of many models and their solution techniques (Tabucanon, 1988:1). Models that accommodate consideration of multiple objectives or multiple criteria are needed in order to make complex decisions. In recent years, MCDM methodology has come into

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prominence, and its tools and techniques have been developed and applied to a myriad of decision problems.

The process of decision-making is the selection of a course of action that will produce optimal results under some criteria of optimization (Tabucanon, 1988:4). Before the problem can be considered well defined, however, the set of alternatives and the set of criteria first have to be known and established. Only then can the selection process commence. What makes MCDM complex is the plurality of the criteria involved in the problem. A problem can be considered amenable to solution using MCDM if and only if there appear at least two conflicting criteria and there are at least two alternative solutions (Tabucanon, 1988:5).

In order to understand the fundamentals of MCDM, some definitions must be provided. Attributes are characteristics used to describe a thing, and they can be objective (e.g. age) or subjective (e.g. prestige) (Tabucanon, 1988:8). Objectives are aspirations that also indicate directions of improvement of selected attributes (e.g. maximize profit), and they do not require the decision-maker to specify their levels (Tabucanon, 1988:8). The limits of achievements of these objectives are defined by the constraints. Goals, like objectives, are aspirations that also indicate direction of improvement of selected attributes, however, desired levels of the attribute are given "a priori" (e.g. maximize profit of at least $10M) (Tabucanon, 1988:8). Criteria are measures, rules, and standards that frame and guide the decision-making (e.g. cost).

Every MCDM problem involves conflicting objectives that may be of varying importance to the decision-maker. Some objectives can be of overriding importance, while some are considered to be less significant than others. In assessing degrees of

importance of multiple criteria, many methods depend heavily or entirely on the judgements of people, whether an individual or group. Opinion measurement includes a variety of methods, such as surveys or panels, in order to extract information from a single individual or to accumulate information from a number of persons who are often experts in the area of interest (Tabucanon, 1988:17). Through elicitation of these opinions and preferences, relative importance of criteria and alternatives may be expressed in terms of weight. Use of weights and formal comparison structures permit alternative rank to be determined.

Despite the considerable diversity in MCDM models, there are some general features that are shared by all. These features include the following: the decision-maker faces a certain choice problem; the decision-maker is assisted by an analyst (person/machine) who has the task of providing scientific assistance; the decision-maker evaluates the alternatives by means of a certain set of criteria; the analyst has at his/her disposal information about the instruments to realize the criteria as well as the impacts of the decision instruments on the criteria; the criteria and instruments have been operationally defined and the objectives are at least ordinally (i.e. ranking scale) measurable (Tabucanon, 1988:34).

Chan expressed such features analytically. Chan instructed that a MCDM problem involves four elements: 1) an alternative set $\mathbf{X}$, with elements x which can be infinite, 2) a criteria set $\mathbf{f}=(f_1,\ldots,f_q)$, 3) an outcome of each choice, $f(\mathbf{x})=[f_1(x),\ldots,f_q(x)]$, or collectively $\mathbf{Y}=\{y\}=\{f(\mathbf{x}) \mid \mathbf{x}\in \mathbf{X}\}$, where $f(\mathbf{x})$ can be a deterministic or random variable, and 4) a preference structure with which the decision-maker picks the best outcome $\mathbf{y}^*\in \mathbf{Y}$ corresponding to the choice $\mathbf{x}^*\in f^{-1}(\mathbf{y}^*)$ (Chan handout, 1998). Understanding

these four elements and the application methods for real-world decisions provide the decision-maker with a powerful tool for selecting among alternatives.

Analytic Hierarchy Process. Behavioral scientists have spent many years studying the human mind and how it makes decisions. They have found that humans are influenced by their previous experiences and this causes them to have biases (DSS, 1983:xv). Basic instincts, preferences and environmental factors also play roles in how we analyze data and make decisions. There is no way to remove these factors from human decision-making, nor would we necessarily want to, but as the problems of our world become more and more complex, it is necessary for us to employ a framework to help make more logical and less biased decisions while still taking our feelings and intuition into consideration (DSS, 1983:xv).

One structured approach to solving MCDM problems that employs such a logical framework is the Analytic Hierarchy Process (AHP). The AHP provides users with the tools to construct decision frameworks for both routine and non-routine problems and provides a means to include value judgements in these decision frameworks (DSS, 1983:xv). This framework is a hierarchy, used to organize all the relevant factors to solve a problem in a logical and systematic way, from the goal to the criteria to the sub-criteria and so on down to the alternatives of decision. The user must define the problem and determine all relevant issues (criteria) in constructing the hierarchy.

The AHP is a flexible and powerful MCDM technique that helps the user with the following: organize complexity; incorporate quantitative information as well as knowledge and intuition based on years of experience; consider trade-offs among competing criteria; synthesize from the goal to determine the best alternatives;

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communicate the rationale for the decision to others; and, incorporate group judgements (if applicable) (DSS, 1983:15). The AHP empowers analysts and decision-makers to be able to relate intangibles to tangibles, the subjective to the objective, and to link both to their purposes. The AHP offers a way to integrate complexity, set appropriate objectives, establish objective priorities, and determine the overall value of each alternative solution. The AHP uses hierarchical decision models and is founded on sound mathematical principles (as discussed in Chapter 3).

Some basic definitions may be helpful in understanding the AHP. A model is a representation of a phenomena, and is used to simplify a situation and solve problems (DSS, 1983:183). A hierarchy is a stratified dominance structure for representing the spread of influence among objectives and criteria for a problem. A decision hierarchy is a hierarchy comprised of a goal, criteria or objectives, and alternatives of choice (DSS, 1983:183).

In arriving at solutions to various problems, the AHP utilizes a seven-step decision process. This process includes the following: problem definition and research; eliminating infeasible alternatives; structuring a hierarchy; making pair-wise judgements (establishing weights); synthesizing results of judgements (determining alternative value); examining and verifying the decision; and, documenting the decision (DSS, 1983:184). The AHP is a proven procedure with a wide range of application; it is easily explained to the decision-maker and tends to be well received due to its intuitive approach to decision-making. The overall flexibility of the methodology led to its selection as the method of choice for expedient site characterization technology alternative and risk assessment/risk-based corrective action method selection.

III. METHODOLOGY

A. Introduction

This chapter begins with a qualitative introduction to the principles of the AHP and some of its advantages. Next, quantitative theory is introduced and developed through use of examples. Following theory is the justification for selection of the decision-maker and the decision-making process utilized by the "decision-maker" in this study. In closing, descriptions of the hierarchies, criteria, and alternatives utilized in the selection of innovative site characterization technology alternatives and a risk assessment/risk-based corrective action method alternatives are presented.

B. Analytic Hierarchy Process

In a complex environment (such as the environment of a decision-maker dealing with sites in Korea) there is a need for a method to cope with the myriad factors that affect the achievement of goals, the solution of problems, and the consistency of judgements (Saaty DML, 1982:1). The AHP is one such method of helping to solve complex problems.

The AHP is a method of breaking down a complex, unstructured situation into its component parts; arranging these parts or variables into a hierarchic order; assigning numerical values based on subjective or objective judgements of the relative importance of each variable; and, synthesizing the judgements to determine which variables have the highest priority and should be acted upon to decide what course of action to take (Saaty DML, 1982:5).

The AHP has three principles of analytic thought as its foundation: the principle of constructing hierarchies, the principle of establishing priorities, and the principle of logical consistency (Saaty DML, 1982:17). The principle of constructing hierarchies involves breaking down reality into its constituent parts and further sub-dividing these parts into smaller, more detailed parts. The number of parts considered for a problem usually ranges between five and nine (Saaty DML, 1982:17). In this manner, the decision-maker is able to integrate large amounts of information into the structure of a problem, permitting a more complete picture of the whole system.

The principle of establishing priorities is built upon the premise that humans have the ability to perceive relationships among things they observe, to compare pairs of similar things against certain criteria, and to discriminate between both members of a pair by judging the intensity of their preference for one over the other (Saaty DML, 1982:17). In so doing, they synthesize their judgements and gain a better understanding of the whole system.

The principle of logical consistency has two components. The first component is that similar ideas or objects are grouped according to homogeneity and relevance (Saaty DML, 1982:18). For example, a grape and a marble can be grouped into a homogeneous set if roundness is the relevant criterion but not if flavor is the criterion. The second component is that the intensities of relations among ideas or objects based on a particular criterion justify each other in some logical way (Saaty DML, 1982:18). Thus, if sweetness is the criterion and honey is judged to be five times sweeter than sugar, and sugar twice as sweet as molasses, then honey should be taken to be ten times sweeter than molasses.

In utilizing these three principles, the AHP incorporates both the qualitative and quantitative aspects of human thought: the qualitative, to define the problem and its hierarchy and the quantitative, to express judgements and preferences concisely (Saaty DML, 1982:18). The process itself is designed to integrate these dual aspects. The AHP is a flexible tool for decision-making and several of its advantages are illustrated in Figure 10.

Unity:
The AHP provides a single, easily understood, flexible model for a wide range of unstructured problems

Process Repetition:
The AHP enables people to refine their definition of a problem and to improve their judgment and understanding through repetition

Complexity:
The AHP integrates deductive and systems approaches in solving complex problems

Judgment and Consensus:
The AHP does not insist on consensus but synthesizes a representative outcome from diverse judgments

Interdependence:
The AHP can deal with the interdependence of elements in a system and does not insist on linear thinking

Tradeoffs:
The AHP takes into consideration the relative priorities of factors in a system and enables people to select the best alternative based on their goals

Hierarchical Structuring:
The AHP reflects the natural tendency of the mind to sort elements of a system into different levels and to group like elements in each level

Synthesis:
The AHP leads to an overall estimate of the desirability of each alternative

Measurement:
The AHP provides a scale for measuring intangibles and a method for establishing priorities

AHP

Consistency:
The AHP tracks the logical consistency of judgments used in determining priorities

Figure 10. Advantages of the Analytic Hierarchy Process (Saaty DML, 1982:23)

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C. Analytical Development

The AHP analysis process begins with a comparison of criteria with respect to the overall goal. The decision-maker determines the weight ratio in order to show the relative importance for every possible pair of criteria. An outline of the pairwise comparison scale as developed by Saaty is shown in Table 11.

Table 11. The Pairwise Comparison Scale (Saaty DML, 1982:78)

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgement slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgement strongly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgements	Compromise is needed between two judgements
Reciprocals	If activity i has one of the preceding numbers assigned to it when compared to activity j, then j has the reciprocal value when compared to i	

As stated, the decision-maker utilizes this pairwise comparison scale in determining weight ratios. An example of these weight ratios is shown in Table 12, where w_{12} shows the relative importance of criterion 1 against criterion 2. In general $w_{ij} = w_i/w_j$ in the matrix $\mathbf{W} = [w_{ij}]_{qxq}$.

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Table 12. Pairwise Comparison of Criteria

Criteria	1	2	3
1	w_1/w_1	w_1/w_2	w_1/w_3
2	w_2/w_1	w_2/w_2	w_2/w_3
3	w_3/w_1	w_3/w_2	w_3/w_3

Now, given the pairwise-comparison ratios w_{ij}, the weights should satisfy the following set of equations:

$$
\begin{aligned}
w_{11}w_1 &+ w_{12}w_2 + w_{13}w_3 &= q'w_1 \\
w_{21}w_2 &+ w_{22}w_2 + w_{23}w_3 &= q'w_2 \\
w_{31}w_3 &+ w_{32}w_3 + w_{33}w_3 &= q'w_3 \\
w_1 &+ w_2 \quad + w_3 &= 1
\end{aligned}
$$

where q' is the eigenvalue and w is the eigenvector in the above equation set $\mathbf{W}\mathbf{w} = q'\mathbf{w}$ or $(\mathbf{W}-q'\mathbf{I})\mathbf{w} = 0$ (Chan text, 1998:5-27).

Matrix $\mathbf{W}$ is consistent if $w_{ij} = w_{ji}^{-1}$ and $w_{ij} = w_{ik}w_{kj}$, or criterion i is preferred to j the same way as criterion j is preferred to criterion i (Chan text, 1998:5-26). In decision-making problems, knowledge of consistency is often important since decision-makers may not want the decision to be based upon judgements that exhibit such low consistency that they appear random (Saaty DML, 1982:84). A certain degree of consistency in setting priorities for elements or activities with respect to some criterion is necessary to get valid results. The AHP measures the overall consistency of judgements by means of a consistency ratio (Saaty DML, 1982:83). In the above example, where matrix $\mathbf{W}$ is composed of three criteria, q' = 3 if everything is consistent. However, if an interview with the decision-maker yields a matrix $\mathbf{W}'$ (instead of $\mathbf{W}$) and the eigenvalue is 3.5, the weights by the decision-maker are inconsistent (Chan text, 1998:5-27). The bigger the eigenvalue is, the larger the inconsistency (Chan text, 1998:5-27).

The same set of simultaneous equations can be defined for analyzing the univariate value functions $v_i(y_i)$, where the weight eigenvalue $\mathbf{w} = (w_1,\ldots,w_q)^T$ is now replaced by the scores of alternatives j on criterion i, $v_i = (v_i^1,\ldots,v_i^{|J|})$, where J is the number of alternatives (in lieu of q, the number of criteria), and $0 \leq v_{ij} \leq 1$ (just as $0 \leq w_{ij} \leq 1$).

In order to outline the AHP methodology, Chan employed the technique in siting a hazardous facility (Chan text, 1998:5-27-29). The 'best' site is evaluated with respect to the risk (R), performance (P), and schedule-of-completion (S), resulting in the weights $[w_{ij}]$ shown in Table 13.

Table 13. Facility Siting Criteria Comparison (Chan text, 1998:5-27)

Best Site:	risk	performance	schedule
risk	1	1/3	2
performance	3	1	3
schedule	1/2	1/3	1

In a similar manner, the three candidate sites (alternatives) A, B and C are evaluated via pairwise comparisons with respect to the three criteria, resulting in the weights $[w_i^J]$ shown in Table 14.

From the criteria comparison of Table 14, the weight eigenvector $\mathbf{w} = (w_R, w_P, w_S)$ and the eigenvalue q'_{max} can be calculated for the best site. The following set of equations may be used in determining $\mathbf{w}$ and q'_{max}:

$$
\begin{aligned}
1w_R + 1/3w_P + 2w_S &= q'w_R \\
3w_R + 1\,w_P + 3w_S &= q'w_P \\
1/2w_R + 1/3w_P + 1w_S &= q'w_S \\
w_R + w_P + w_S &= 1
\end{aligned}
$$

Table 14. Facility Siting Alternative Comparison (Chan text, 1998:5-28)

Risk	A	B	C
A	1	1/3	2
B	3	1	3
C	1/2	1/3	1
Performance	A	B	C
A	1	1/3	2
B	3	1	3
C	1/2	1/3	1
Schedule	A	B	C
A	1	1/3	2
B	3	1	3
C	1/2	1/3	1

While the simultaneous equation set can be solved explicitly, the weight eigenvector **w** can now be determined through the following procedure: sum the matrix columns; divide each column element by the column sum; determine a row sum; take the average of each row sum by dividing by the number of columns; this provides **w**. For this example **w** = (0.25, 0.59, 0.16). This process is illustrated below in Table 15.

Table 15. Determination of Weight Eigenvector

Best Site:	R	P	S	Sum:	Avg Sum:	Weight:
R	1/(4.50)	(1/3)/1.67	2/6	0.755	0.755/3	0.25
P	3/(4.50)	1/1.67	3/6	1.765	1.765/3	0.59
S	(1/2)/4.50	(1/3)/1.67	1/6	0.477	0.477/3	0.16

The eigenvalue q'_{max} for this level of the hierarchy can be determined by the following procedure: criteria weights are multiplied by original facility siting criteria; the rows of the resulting matrix are totaled; the row totals are divided by respective criteria weights; the resulting matrix is averaged to provide q'_{max}. The procedure is outlined in Table 16 and Table 17.

Table 16. Intermediate q' Matrix

Best Site:	R (0.25)	P (0.59)	S (0.16)
R	1	1/3	2
P	3	1	3
S	1/2	1/3	1

Table 17. Determination of q'

Best Site:	R	P	S	Row Total:	q'	q'
R	0.25	0.19	0.32	0.76	0.76/0.25	3.04
P	0.75	0.59	0.48	1.82	1.82/0.59	3.08
S	0.12	0.19	0.16	0.47	0.47/0.16	2.94

Now, $q'_{max} = (\Sigma_k \, q')/k$, which equals the average q' as determined above. Thus,

$$q'_{max} = (3.04 + 3.08 + 2.94)/3 = 3.02.$$

The consistency index (CI) can be determined from the following equation:

$$CI = (q'_{max} - q)/(q-1)$$

In this example, q'_{max} has been determined to be 3.02 and q equals 3.00. Thus, the CI is determined to be .01, which indicates excellent consistency.

A composite value function of additive form that includes all the component univariate-value functions of risk (R), performance (P) and schedule (S) can now be written. This equation is presented as follows: $v = 0.25v_R + 0.59v_P + 0.16v_S$, where v is the overall value of an alternative, and v_R, v_P, and v_S are the corresponding value of the alternative with respect to risk, performance, and schedule of completion, respectively.

Computation of the eigenvector $\mathbf{v_I} = (v_I^A, v_I^B, v_I^C)$ and eigenvalue q'_{max} for each of the criteria I = R, P and S, follows. The representative equations, obtained from the data in Table 14, are derived for illustrative purposes.

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Eigenvector and eigenvalue computations for risk (R) criterion:

$$
\begin{aligned}
1v_R{}^A &\quad +1v_R{}^B &\quad + 2v_R{}^C &\quad = q'_R v_R{}^A \\
1v_R{}^A &\quad + 1v_R{}^B &\quad + 2v_R{}^C &\quad = q'_R v_R{}^B \\
\tfrac{1}{2}v_R{}^A &\quad + \tfrac{1}{2}v_R{}^B &\quad + 1v_R{}^C &\quad = q'_R v_R{}^C \\
v_R{}^A &\quad + v_R{}^B &\quad + v_R{}^C &\quad = 1
\end{aligned}
$$

Hence, $v_R=(v_R{}^A, v_R{}^B, v_R{}^C)=(0.4,0.4,0.2)$, $q'_{Rmax}=3$, and CI=0. These computations were performed in the same manner as the previous criterion computations.

Eigenvector and eigenvalue computations for performance (P) criterion:

$$
\begin{aligned}
1v_P{}^A &\quad +3v_P{}^B &\quad + 9v_P{}^C &\quad = q'_P v_P{}^A \\
1/3v_P{}^A &\quad + 1v_P{}^B &\quad + 1/7v_P{}^C &\quad = q'_P v_P{}^B \\
1/9v_P{}^A &\quad + 7v_P{}^B &\quad + 1v_P{}^C &\quad = q'_P v_P{}^C \\
v_P{}^A &\quad + v_P{}^B &\quad + v_P{}^C &\quad = 1
\end{aligned}
$$

Hence, $v_P=(v_P{}^A, v_P{}^B, v_P{}^C)=(0.701,0.084,0.215)$, $q'_{Pmax}=4.12$, and CI=0.56.

Eigenvector and eigenvalue computations for schedule (S) criterion:

$$
\begin{aligned}
1v_S{}^A &\quad +3v_S{}^B &\quad + 1/9v_S{}^C &\quad = q'_S v_S{}^A \\
1/3v_S{}^A &\quad + 1v_S{}^B &\quad + 1/7v_S{}^C &\quad = q'_S v_S{}^B \\
1/9v_S{}^A &\quad + 7v_S{}^B &\quad + 1v_S{}^C &\quad = q'_S v_S{}^C \\
v_S{}^A &\quad + v_S{}^B &\quad + v_S{}^C &\quad = 1
\end{aligned}
$$

Hence, $v_S=(v_S{}^A, v_S{}^B, v_S{}^C)=(0.138,0.072,0.79)$, $q'_{Smax}=3.205$, and CI=0.103.

Based upon the composite value function, $v = 0.25v_R + 0.59v_P + 0.16v_S$, and the eigenvectors, $v_I = (v_I{}^A, v_I{}^B, v_I{}^C)$, calculated above, the sites (alternatives), A, B and C, can now be rank ordered. This rank ordering identifies alternative preference, and is shown below.

$$
\begin{aligned}
v^A &= \quad 0.25v_R{}^A &\quad + 0.59v_P{}^A &\quad +.16v_S{}^A &\quad =0.537 \\
v^B &= \quad 0.25v_R{}^B &\quad + 0.59v_P{}^B &\quad +.16v_S{}^B &\quad =0.161 \\
v^C &= \quad 0.25v_R{}^C &\quad + 0.59v_P{}^C &\quad +.16v_S{}^C &\quad =0.302
\end{aligned}
$$

From the calculated value functions, it is noted that site A is preferred to site C, which in turn is preferred to site B. Note that the univariate utility functions v_R, v_P and v_S need not

be determined precisely as only point estimates of v_I's are necessary (Chan text, 1998:5-29).

Based upon the computed eigenvalues, q_R, q_P and q_S, and the respective CIs, comments can now be made concerning the consistency of the decision-maker and the corresponding validity of the alternative ranking (Chan text, 1998:5-29). Inconsistent interview results are apparent with the performance and schedule criteria, both exceeding the CI maximum of 0.10 set by Saaty (Chan text, 1998:5-29). Poor consistency reflects the validity of the decision-makers's responses during the interview, and provides a measure of the independence among criteria. CI values above 0.10 question the reliability of the ranking among alternatives, and if they are deemed unacceptable, the anlayst must redefine the criteria and conduct required follow-up interviews to obtain a more reliable ranking (Chan text, 1998:5-29).

D. ExpertChoice Model

The AHP has been successfully incorporated into several software packages. The software package ExpertChoice, which employs the AHP, has been used to solve multiple criteria decision problems (Tiley, 1994:26). In this work, the software package was employed as the method of choice in ranking site characterization technology alternatives and risk assessment/RBCA method alternatives. The ExpertChoice model organizes the various elements of a problem into a hierarchy similar to a family tree structure. Each element in a tree is called a node. The top level contains the goal node (Z space). Intermediate levels represent the factors or criteria of the problem (Y Space). At the bottom of the tree are the leaves, which represent the alternatives of choice (X

Space) (DSS, 1983:3). The goal, criteria, and alternatives for an example site

characterization technology hierarchy produced by ExpertChoice are shown in Figure 11.
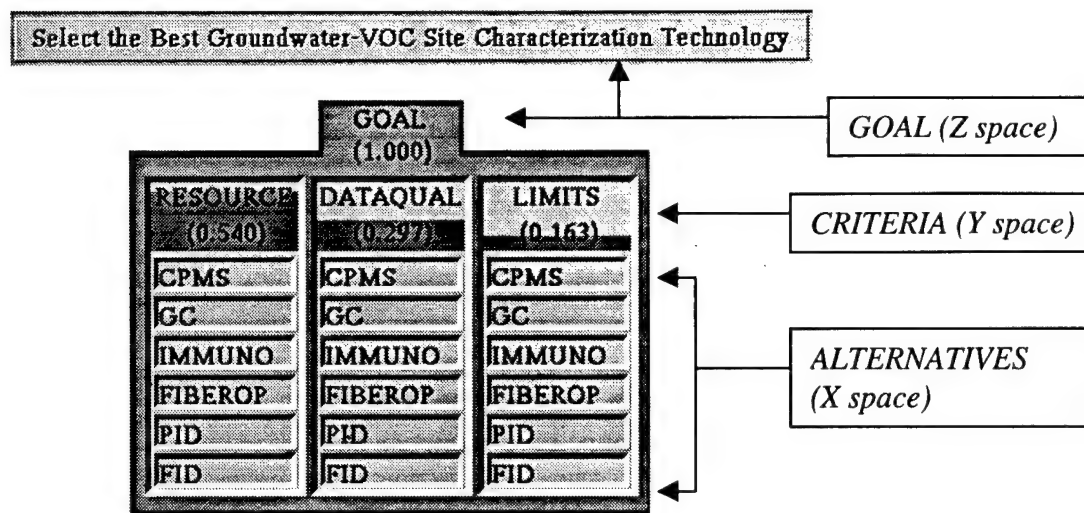
Figure 11. Example ExpertChoice Hierarchy for Selection of a Site Characterization Technology

E. Decision-Maker Selection

Griffin, in a companion thesis effort, defined the decision-maker as the

organization, activity, or agency appointed to create, implement, and monitor policy in

regards to environmental compliance and remediation actions (Griffin, 1999:32). He

noted that DODI 4715.5 requires the Deputy Under Secretary of Defense for

Environmental Security to "designate a DoD Component as the DoD Environmental

executive agent for environmental matters in foreign countries." An executive agent is an

agency assigned by the DoD to oversee specific activities in a foreign country, and the

areas of environmental compliance and restoration represent such activities. He reported

that within DODI 4715.5, the Commander-in-Chief of US Forces in Korea

(CINCUSFORKOREA) is appointed as the executive agent for the Pacific Command

forces in the ROK (Griffin, 1999:32). With the US Forces Korea Environmental Policy

Office (USFK-EPO) having been designated by the CINCUSFORKOREA as his/her executive agent, this office was selected as the decision-maker for evaluation of field-based site characterization technology and risk assessment/RBCA method alternatives which will "best" serve the needs of the unique environment within the ROK.

The decision-maker for this research effort is an individual from the USFK-EPO staff. This individual would be directly involved in any future site characterization and risk assessment policy decisions, and would be involved in implementation of future remediation policy in the ROK. The original intention was for the "decision-maker" to be comprised of a group of individuals. This "decision-making team" was to be comprised of two members from the USFK-EPO Office and one member from the US Army Corps of Engineers-Far East District (USACE-FED). This arrangement was recommended by the head of USFK-EPO in order to ensure expertise in the areas of both policy and technology during the AHP evaluation process (Anderson, 1998). Due to extenuating circumstances, no group effort was performed, and the single decision-maker completed the AHP survey.

F. Description of Hierarchies

The decision-maker determined that development of an intelligent site characterization plan for DoD sites in Korea would best be served by separating the hierarchies according to site type, contaminant type and media type (Anderson, 1998). The site types included vulnerable and non-vulnerable sites. Vulnerable sites are those where access is unlimited, pathways to receptors are evident, and potential impact to large populations exist. Non-vulnerable sites are those with limited access, pathways to receptors is questionable, and the site is remote from population centers.

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Mirroring categories outlined in the Environmental Protection Agency (EPA) Manual *Field Analytical and Site Characterization Technologies: Summary of Applications*, hierarchies were further developed for the two primary media of groundwater and soil, and for the six primary contaminant categories of VOCs, SVOCs, fuels, inorganics, explosives, and pesticides. This resulted in 24, site-, media-, and contaminant-specific site characterization technology hierarchies. Table 18 provides a list of the descriptors utilized in constructing the various field-based site characterization technology selection hierarchies.

The decision-maker was also interested in developing a hierarchy for a risk assessment/risk-based corrective action method (Anderson, 1998). Three methods were previously described. These methods include the ASTM RBCA method, the DoD Relative Risk method, and the state of Hawaii RBCA method.

G. Description of Criteria

Three criteria were developed for analysis and approved by the decision-maker in order to evaluate potential site characterization technologies (Anderson, 1998). These criteria included resources, data quality, and method limitations, respectively. Resources included equipment and material costs and per sample costs, as applicable, as well as the sampling/analysis time associated with implementation of the particular technology. Data quality includes the type of data produced by the technology (qualitative, semi-quantitative, or quantitative), technology accuracy and technology precision. Method limitations include the method detection limits and dynamic range, geologic/hydrogeologic limitations, and any other pertinent technology constraints.

Media	Contaminant	Alternatives
groundwater	VOC	Immunoassay, GC with Detector, Cone Penetrometer Mounted Sensor, Biosensors, FID, PID, Colorimetric Indicators
groundwater	SVOC	Immunoassay, GC with Detector, Cone Penetrometer Mounted Sensor, Biosensors, Colorimetric Indicators
groundwater	Fuel	Immunoassay, GC with Detector, Cone Penetrometer Mounted Sensor, Biosensors, FID, PID, Colorimetric Indicators
groundwater	Inorganics	Immunoassay, X-ray Fluorescence, Anodic-Stripping Voltammetry, Biosensors, Graphite Funrnace Atomic Absorption, Colorimetric Indicators
groundwater	Explosives	Immunoassay, Biosensors, Colorimetric Indicators
groundwater	Pesticides	Immunoassay, GC with Detector, Biosensors, Colorimetric Indicators
soil	VOC	Immunoassay, GC with Detector, Cone Penetrometer Mounted Sensor, Biosensors, FID, PID, Colorimetric Indicators
soil	SVOC	Immunoassay, GC with Detector, Cone Penetrometer. Mounted Sensor, Biosensors, Colorimetric Indicators
soil	Fuel	Immunoassay, GC with Detector, Cone Penetrometer Mounted Sensor, Biosensors, FID, PID, Colorimetric Indicators
soil	Inorganics	Immunoassay, X-ray Fluorescence, Anodic-Stripping Voltammetry, Biosensors, Graphite Funrnace Atomic Absorption, Colorimetric Indicators
soil	Explosives	Immunoassay, Biosensors, Colorimetric Indicators
soil	Pesticides	Immunoassay, GC with Detector, Biosensors, Colorimetric Indicators

Three criteria were developed for analysis and approved by the decision-maker in order to evaluate risk assessment method alternatives (Anderson, 1998). The three criteria include policy, required method input, and expected method output. Policy includes the ability of the method to meet CONUS DoD and USFK risk assessment policy requirements. Method input includes the level of data and extent of resources required as input to the method in order to develop a useful risk assessment/RBCA plan.

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Method output includes the ability of the method to produce a risk assessment/RBCA

plan that meets the decision-maker's stated needs.

H. Description of Alternatives.

The 11 innovative site characterization technologies and 3 risk assessment/RBCA

methods evaluated were previously described in detail within the literature review. The

innovative site characterization technologies include immunoassay, x-ray fluorescence,

gas chromatography with detector, anodic-stripping voltammetry, cone penetrometer

mounted sensor systems, biosensors, graphite furnace atomic absorption, flame ionization

detector, fiber-optic chemical sensor, photoionization detector, and colorimetric

indicators. The risk assessment methods include the ASTM RBCA method, the DoD

Relative Risk method, and the state of Hawaii RBCA method.

IV. RESULTS

A. Introduction

A literature, site visit, and interviews were accomplished to obtain the data and information necessary to complete this research effort. A summary report of the site visit to the ROK is at Appendix 4. The literature review and applicable appendices present a compilation of relevant information for use by DoD decision-makers in the ROK in developing conceptual models for future implementation of expedient site characterization and risk assessment/RBCA methods.

In particular, a detailed AHP survey was completed by the decision-maker in order to evaluate field-based site characterization technologies and risk assessment/RBCA methods and select the most preferred alternatives. The completed AHP survey is at Appendix 3. The host of remaining research questions was answered through the interview and literature review process. The results to follow addressed all research questions as well as the stated needs of the decision-maker in the ROK.

B. Site Characterization

The focus of the initial research question was to determine the primary sources of contamination and the relative proportions of the various contaminants in relation to the known sites at DoD installations in the ROK. A compilation of the available information used to formulate an answer to this question is at Appendix 1.

The primary sources of contamination were separated into three broad categories. System failures or system component failures (e.g. UST product feed line to boiler unit breaks) account for 68 percent of the sources of contamination. Accidental spills and

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releases (e.g. contractor overfill of diesel fuel heating supply tank), with the problem related to human error, account for 23 percent of the sources of contamination. The remaining 9 percent of the sources of contamination are due to unknown causes (e.g. VOCs disCVered in drinking water with no apparent source) or due to practices which were acceptable in the past (e.g. historic contamination from the 1970's or before).

Two approaches were used in order to determine the primary classes of contaminants expected to be found at the various DoD installations. The first approach included the collection of all available information on the various locations and types of contamination, including areas of potential contamination, formerly investigated sites, and spill or release locations, and then formulating general statements through extrapolation of this data to DoD installations as a whole. The available data showed that fuel-related contaminants comprise 70 percent of known contaminants, VOCs account for 22 percent of known contaminants, SVOCs account for 6 percent of known contaminants, while inorganics, pesticides and unknowns account for the remaining 2 percent. Of the 70 percent related to fuel contamination, 65 percent were attributed to diesel, 21 percent were attributed to JP-4/JP-8/JPTS, while the remaining 14 percent were attributable to miscellaneous POLs and vehicle gasoline (MOGAS).

The second approach utilized data from the Defense Reutilization and Marketing Organization (DRMO) annual waste disposal summaries from 1996 to 1998. The data are summarized at Appendix 1. Correlation between hazardous materials use and hazardous waste disposal can used to infer which contaminants may potentially be released into the environment.

Site visits conducted at the various installations provided all applicable site characterization information. The amount of available information, as expected, was quite sparse. It was readily apparent that the USAF has been able to obtain some resources in order to perform limited site investigations, while the USA has met with little success in obtaining such resources.

Osan Air Base addressed the requirements for remediation within the Osan Air Base General Plan, and had access to basic site characterization data on approximately 10 sites previously investigated by the USACE-FED, private contractor, or in-house personnel; however, the 240th CEF, based at Buckley Air National Guard Base, CO, completed a report which compiled all known site characterization data. This report was the Osan Air Base Restoration Management Action Plan, and included site contamination, site characterization, and site restoration data and information on over 40 formerly identified sites and new areas of concern.

Kunsan Air Base utilized a private contractor to complete the Installation Wide Environmental Baseline Assessment, Kunsan Air Base, Republic of Korea, a document addressing in excess of 22 operational areas or facilities with expected contamination. This document contains varying degrees of site characterization data and information. The same contractor performed detailed site characterization and risk assessment at five of those areas or facilities identified in the baseline assessment, and reported results in Five Site Investigations, Kunsan Air Base, Republic of Korea.

The USA had no formal reports available, although official memorandums and informal memorandums were available for several problem sites. Little or no site characterization data or information could be interpreted from these documents, as they

were recorded primarily to report the problem or initial findings or report the status of impromptu remedies being tried.

In addition to site characterization data provided by the various installations, the USACE-FED completed and provided a geologic profile summary of the ROK. This information is at Appendix 4. The data from this geologic profile can be utilized as a broad constraint in technology application decision-making as well as making inferences in order to help develop initial conceptual models for sites.

From these findings, the only DoD installations in the ROK that have data capable of supporting some scale of cost estimation and risk assessment or RBCA level determination are Osan Air Base and Kunsan Air Base. The decision-maker, in determining appropriate site characterization technologies and selecting risk assessment/RBCA methods, in essence determines what additional site characterization data are required. For those installations with no data, an inventory of areas of concern or potentially contaminated areas must first be compiled. Once compiled, technologies can be selected and implemented based upon site characteristics and decision-maker preferences. For those sites with some 'intermediate' degree of data and information, the decision-maker can decide if existing data are sufficient or if supplemental data are required in order revise cost estimates and set RBCA levels.

Three criteria were developed for analysis and approved by the decision-maker in order to evaluate and select among the various field-based site characterization technologies applicable for use at DoD installations in the ROK. These criteria included resources, data quality, and method limitations. Resources included equipment and material costs and per sample costs, as applicable, as well as the sampling/analysis time

associated with implementation of a particular technology. Data quality includes the type of data produced by the technology (qualitative, semi-quantitative, or quantitative), technology accuracy and technology precision. Method limitations include the method detection limits and dynamic range, geologic/hydrogeologic limitations, and any other pertinent technology constraints.

The field-based site characterization technologies readily available for use at DoD installations in the ROK were selected from USEPA sources, from NHSRC sources, from USAF AFRL resources, and through a comprehensive literature review. The technologies ultimately selected for evaluation include immunoassay, x-ray fluorescence, gas chromatography with detector, anodic-stripping voltammetry, cone penetrometer mounted sensor systems, biosensors, graphite furnace atomic absorption, flame ionization detector, fiber-optic chemical sensor, photoionization detector, and colorimetric indicators. While the author does not intend to imply that the technologies evaluated include all applicable technologies, these technologies do represent the body of those with significant literature support and the backing of available field data. The world of site characterization using field-based instrumentation is a dynamic one, and new products and new techniques continue to be disCVered.

Technologies potentially available for future use are described as emerging technologies in the literature review. These technologies include the E-FAST, developments in capillary electrophoresis, direct push platforms and VOC detection (primarily halogenated VOCs), direct push platform vision probe system, the sonic cone penetrometer, the cone penetrometer and X-ray fluorescence, and an overview of potential detection methods and sensor suite development initiatives for the Geoprobe®

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and CPT. As with the list of innovative technologies, this list is not all-inclusive and the reader is encouraged to explore additional innovations in this dynamic field. With the presence of economic, regulatory, and entrepreneurial incentives to promote development, the field of emerging technologies and techniques will continue to be flush with new entries.

The costs and corresponding capabilities of the various innovative field-based technologies were discussed in-depth within the literature review. The intent of the literature review was to provide relevant cost ranges in the various media under various conditions as well as capability ranges in the various media under various conditions. In this manner, the decision-maker had adequate data and information in order to objectively and subjectively evaluate the applicable alternatives for the various site type, media type, and contaminant type.

As discussed in the literature review and demonstrated in the methodology, the AHP was utilized to capture relevant decision-maker preferences concerning the various innovative site characterization technologies. A comprehensive pair-wise comparison survey was constructed based upon the work of Saaty and as demonstrated by the ExpertChoice software system. A brief example is provided within the survey at Appendix 3.

The procedure begins by constructing the hierarchy as discussed within the methodology. Once completed, pair-wise assessments can be performed. Pair-wise assessments begin with a comparison of criteria with respect to the goal. Using the ExpertChoice software, the comparison type is based upon the decision-maker-determined importance of each criterion versus the others (until all pair-wise comparisons

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have been exhausted). The mode utilized in the software was the numerical questionnaire, which creates a table exactly like that shown at Appendix 3 (e.g. Figure 3-3). In this manner, importance is indicated by merely selecting the appropriate box, which the software highlights for identification. Once all comparisons have been completed, criteria weights are calculated and displayed, while the resulting inconsistency of the choices is also calculated and displayed.

In a similar way, alternatives are evaluated in a pair-wise manner with respect to each of the criteria. In this case the comparison type involves the preference of one alternative versus another with respect to the specific criteria. The preference comparison type allows the decision-maker to utilize objective data (from the literature) and subjective data (personal opinion/experience/bias) in comparing various alternatives and determining resulting preference intensities. As with the criteria comparison with respect to the goal, the numerical questionnaire software option was utilized to select and record decision-maker preferences.

Through transfer of decision-maker data into the ExpertChoice software system in the manner described, innovative site characterization technologies were ranked in order of preference according to the specific decision-maker. The results for innovative technology evaluation are shown in Tables 19 through 26. Tables 19 through 22 report alternative preferences for soil contamination at vulnerable and non-vulnerable sites. Tables 23 through 26 report alternative preferences for groundwater contamination at vulnerable and non-vulnerable sites.

Table 19. Technology Evaluation of Vulnerable Sites with Organic Compound Soil Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	FID[7]	PID[8]	CPMS[9]	Biosen[10]
VOC	.143	.429	.429	.279	.193	.116	.154	.102	.085	.070
SVOC	.143	.429	.429	.401	.291	.180	---	---	.116	.083
Fuel	.143	.429	.429	.166	.125	.068	.116	.114	.360	.051

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – flame ionization detector alternative
8 – photoionization detector alternative
9 – cone penetrometer mounted sensor platform alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

Table 20. Technology Evaluation of Vulnerable Sites with Inorganic, Explosive, and Pesticide Soil Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	ASV[7]	XRF[8]	GFAA[9]	Biosen[10]
Inorganic	.143	.429	.429	---	.111	.120	.217	.134	.314	.104
Explosive	.143	.429	.429	---	.214	.256	---	---	---	.530
Pesticide	.097	.570	.333	.244	.295	.197	---	---	---	.264

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – anodic stripping voltammetry alternative
8 – X-ray fluorescence alternative
9 – graphite furnace atomic absorption spectroscopy alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

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Table 21. Technology Evaluation of Non-Vulnerable Sites with Organic Compound Soil Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	FID[7]	PID[8]	CPMS[9]	Biosen[10]
VOC	.500	.250	.250	.179	.155	.117	.206	.176	.106	.063
SVOC	.500	.250	.250	.271	.234	.210	---	---	.198	.087
Fuel	.500	.250	.250	.108	.112	.081	.185	.184	.279	.052

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – flame ionization detector alternative
8 – photoionization detector alternative
9 – cone penetrometer mounted sensor platform alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

Table 22. Technology Evaluation of Non-Vulnerable Sites with Inorganic, Explosive, and Pesticide Soil Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	ASV[7]	XRF[8]	GFAA[9]	Biosen[10]
Inorganic	.500	.250	.250	---	.169	.199	.175	.107	.243	.106
Explosive	.500	.250	.250	---	.264	.288	---	---	---	.448
Pesticide	.500	.250	.250	.187	.331	.297	---	---	---	.185

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – anodic stripping voltammetry alternative
8 – X-ray fluorescence alternative
9 – graphite furnace atomic absorption spectroscopy alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

Table 23. Technology Evaluation of Vulnerable Sites with Organic Compound Groundwater Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	FID[7]	PID[8]	CPMS[9]	Biosen[10]
VOC	.105	.605	.290	.283	.175	.145	.127	.095	.094	.080
SVOC	.105	.605	.290	.402	.189	.161	---	---	.166	.082
Fuel	.105	.605	.290	.209	.181	.093	.128	.094	.245	.049

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – flame ionization detector alternative
8 – photoionization detector alternative
9 – cone penetrometer mounted sensor platform alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

Table 24. Technology Evaluation of Vulnerable Sites with Inorganic, Explosive, and Pesticide Groundwater Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	ASV[7]	XRF[8]	GFAA[9]	Biosen[10]
Inorganic	.105	.605	.290	---	.096	.117	.223	.138	.337	.089
Explosive	.105	.605	.290	---	.216	.224	---	---	---	.559
Pesticide	.067	.715	.218	.208	.288	.199	---	---	---	.304

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – anodic stripping voltammetry alternative
8 – X-ray fluorescence alternative
9 – graphite furnace atomic absorption spectroscopy alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

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Table 25. Technology Evaluation of Non-Vulnerable Sites with Organic Compound Groundwater Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	FID[7]	PID[8]	CPMS[9]	Biosen[10]
VOC	.260	.413	.327	.236	.173	.163	.134	.126	.096	.071
SVOC	.260	.413	.327	.346	.214	.176	---	---	.180	.084
Fuel	.260	.413	.327	.185	.174	.096	.165	.127	.204	.050

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – flame ionization detector alternative
8 – photoionization detector alternative
9 – cone penetrometer mounted sensor platform alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

Table 26. Technology Evaluation of Non-Vulnerable Sites with Inorganic, Explosive, and Pesticide Groundwater Contamination

Contaminant	Criteria Weights			Alternative Values						
	Res[1]	DQ[2]	Lim[3]	GC[4]	Color[5]	Immuno[6]	ASV[7]	XRF[8]	GFAA[9]	Biosen[10]
Inorganic	.260	.413	.327	---	.123	.144	.204	.126	.312	.092
Explosive	.260	.413	.327	---	.223	.288	---	---	---	.488
Pesticide	.260	.413	.327	.230	.311	.235	---	---	---	.224

Notes: 1 – criteria of resources
2 – criteria of data quality
3 – criteria of method limitations
4 – gas chromatograph with detector alternative
5 – colorimetric indicator alternative
6 – immunoassay alternative
7 – anodic stripping voltammetry alternative
8 – X-ray fluorescence alternative
9 – graphite furnace atomic absorption spectroscopy alternative
10 – biosensor alternative
highlighted cell indicates the most preferred alternative

C. Risk Evaluation

Risk assessment can take on a myriad of formats and the resulting data and resource requirements depend upon the specific format utilized. The baseline risk assessment, which had been previously referred to as the traditional risk assessment, requires considerable input, but provides a comprehensive, defendable output. Relative risk assessment and risk-based corrective action methods require varying degrees of data depending upon decision-maker needs, and provide varying degrees of output accordingly. The key is to determine a method that meets the needs of the decision-maker, does not unnecessarily waste time and money, and still provides an acceptable output that can be evaluated and acted upon.

The list of software designs and theoretical models that have been utilized to perform risk assessments or establish RBCA levels is quite extensive. However, this researcher, in conjunction with the decision-maker, focused upon the situational-specific constraints and needs of DoD installations in the ROK and selected one risk assessment and two RBCA methods for potential employment. These three methods were described in the literature review, and include the ASTM RBCA method, the DoD Relative Risk Site Evaluation Method, and the state of Hawaii RBCA method.

The input requirements for the three alternatives were discussed in the literature review, and vary according to alternative considered and level of detail within the alternative (e.g. which RBCA tier to implement). Some requirements are common to all methods, such as establishing DQOs, determining potential contaminant(s) of concern, determining relevant exposure pathways, and determining potential receptors.

Requirements for application of the ASTM RBCA method depend heavily on whether Tier 1, Tier 2, or Tier 3 analysis is implemented. In addition to the common requirements mentioned above, the ASTM RBCA method requires establishment of RBSLs for Tier 1. Tier 2 requires the additional determination of SSTLs (which replace the RBSLs) and points of compliance, basic soil properties, and fundamental contaminant fate and transport data. Tier 3 is similar to Tier 2, yet additional aquifer characteristics are collected, soil properties delineated, and more detailed contaminant fate and transport data is determined in order to further revise SSTLs and point(s) of compliance.

The DoD Relative Risk Site Evaluation method is a relative method utilized to evaluate the risk posed by a site in comparison with other similarly assessed sites. Inputs are based on three principal factors, including the contaminant hazard factor (CHF), the migration pathway factor (MPF), and the receptor factor (RF). Factors are based on a quantitative evaluation of contaminants and a qualitative evaluation of pathways and receptors, via groundwater, surface water, sediment and surface soils. The CHF is based on the ratio of the maximum concentration of a contaminant reliably detected in a medium to a RBCV, while the MPF is determined by matching available site data information on pathways with definitions about the likelihood of contaminant migration. RFs are similarly determined by matching receptor information with provided definitions.

The requirements for applying the state of Hawaii RBCA method are similar to the ASTM RBCA method in that they depend upon whether Tier 1, Tier 2, or Tier 3 analysis is implemented. Tier 1 analysis requires loose determination of the areal extent and location of contamination. These data are then compared against prescribed SALs. Tier 2 analysis requires identification of necessary aquifer characteristics and data

concerning the physical and chemical properties of the chemical(s) of concern (basic fate and transport information). These data are used to determine site specific (versus default) SALs. When Tier 3 analysis is invoked, the decision-maker can propose alternate acceptable risk levels (as high as 10^{-4}), accomplishing this through implementation of a detailed fate and transport model, a direct exposure model, and/or an exposure pathway evaluation model.

Each of the various methods have advantages and disadvantages. The various advantages and disadvantages are weighed by the decision-maker prior to ultimately selecting the preferred alternative. A brief discussion of risk assessment and RBCA method advantages and disadvantages follows.

One of the advantages of the ASTM RBCA method lies in its inherent flexibility, in that the method can be applied in lieu of or in conjunction with an existing environmental regulatory framework. The method permits the decision-maker to select the tier to proceed with and thus provides the decision-maker with a large amount of control over site conceptual model development, dynamic workplan implementation, resource expenditures, type and amount of data, and target risk levels. The output, regardless of tier, is a corrective action level (a risk-based cleanup level) that reflects consideration of applicable contaminant(s) of concern, exposure pathways, and potential receptors.

The ASTM RBCA method also has perceived disadvantages. The method incorporates assumptions of acceptable risk (10^{-4} to 10^{-6}) for Tier 1 analysis, which may or may not be acceptable or defendable. The first tier utilizes conservative exposure factors and fate and transport parameters in determination of RBSLs. In addition, if a

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complete traditional risk assessment providing incremental risk as the primary output is the goal, the decision-maker should use a baseline risk assessment method or similar method.

The DoD Relative Risk Site Evaluation Method also has advantages. The method provides a mechanism to rank sites according to objective and subjective data, which permits a more efficient allocation of oversight and other resources. The method is a practical tool to assist in sequencing environmental restoration work. Through incorporation of objective and subjective data in determining relative risk, extensive and costly (and often inefficient) data collection can often be avoided. The method provides a framework that is user-friendly, requiring determination of only three primary input factors, and then following with a comprehensible comparison tool in order to establish relative risk (illustrated in Figures 8 and 9).

The DoD Relative Risk Site Evaluation method has inherent disadvantages as well. The overall output is a relative risk ranking that does not provide a quantitative determination of risk nor does it provide a corrective action level based upon risk. Since the MPF and RF are selected based upon the available information and subjective judgements, personal bias, lack of information, and/or lack of knowledge/experience can significantly affect the relative risk determined for the site. Assumptions built into the framework of the process, such as the RBCVs used in determination of the CHF, definitions specified for the determination of the MPF, and definitions specified for the determination of the RF, may not parallel decision-maker definitions. These considerations limit flexibility, providing potentially overly conservative or under conservative relative risk rankings, depending upon the particular decision-maker.

The state of Hawaii RBCA method has advantages similar to many of those of the ASTM RBCA method. The method provides an inherent flexibility, in that the method can be applied in lieu of or in conjunction with an existing environmental regulatory framework. The method permits the decision-maker to select the tier to proceed with and thus provides the decision-maker with a large amount of control over site conceptual model development, dynamic workplan implementation, resource expenditures, type and amount of data, and target risk levels. The output, regardless of tier, is a corrective action level (a risk-based cleanup level) that reflects consideration of applicable contaminant(s) of concern, exposure pathways, and potential receptors.

The Hawaii RBCA method also is not without some disadvantages. The method is focused heavily on the resource important for that particular state, which is groundwater. In other areas, groundwater may not be the critical resource (such as the sole source of drinking water), dampening the applicability of the method. Critical inputs for this method, such as annual rainfall, may not influence corrective action levels as extensively in arid regions or other climates as heavily as in Hawaii, and thus the decision-maker would have to determine if the foundational concepts of the method are reasonable for their area of concern. Tier 1 and Tier 2 analysis are bound by a 10^{-6} level of attributable risk, which, depending upon pathways, receptors, contaminant, and current and future land use, may or may not be practical.

Three criteria were developed for analysis and approved by the decision-maker in order to evaluate and select the preferred alternative among the one risk assessment and two RBCA methods deemed applicable for use at DoD installations in the ROK. These criteria included policy, required method input, and expected method

output. Policy includes the ability of the method to meet CONUS DoD and USFK risk assessment policy requirements. Method input includes the level of data and extent of resources required as input to the method in order to develop a useful risk assessment/RBCA plan. Method output includes the ability of the method to produce a risk assessment/RBCA plan that meets the decision-maker's stated needs.

As discussed in the literature review and demonstrated in the methodology, the AHP was utilized to capture relevant decision-maker preferences concerning the various risk assessment and RBCA methods. A comprehensive pair-wise comparison survey was constructed based upon the work of Saaty and as demonstrated by the ExpertChoice software system. A brief example of the process is provided within the AHP survey at Appendix 3. The method of AHP analysis was the same as described for the innovative site characterization technology evaluation. A hierarchy was constructed, and pair-wise assessments were performed. Again, the ExpertChoice comparison type for the criteria was importance, while the mode was again the numerical questionnaire. Similarly, the alternatives were then compared against the various criteria, with preference being the comparison type, and the numerical questionnaire utilized as the mode.

Through transfer of decision-maker data into the ExpertChoice software system in the described manner, the risk assessment method and two RBCA methods were ranked in order of preference according to the specific decision-maker. The results for risk assessment/RBCA method evaluation are shown in Table 27.

Table 27. Risk Assessment/RBCA Method Evaluation

Criteria	Criteria Weights	Alternative	Alternative Value
Policy	.455	ASTM RBCA	.452
Method Input	.091	Hawaii RBCA	.452
Method Output	.455	DoD Relative Risk Eval	.096

Note: highlighted cell indicates the most preferred alternative(s)

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V. CONCLUSIONS AND RECOMMENDATIONS

A. Introduction

The overall goals of this proposed research were twofold. The first goal was to develop a method, which is appropriate for use at DoD installations in the ROK, to expeditiously obtain inexpensive site characterization data that can be used for risk analysis as well as refinement of remedial cost estimates. Through incorporation of the accelerated site characterization process, development of dynamic workplans, incorporation of appropriate DQOs, understanding of relevant DQIs, and implementation of appropriate field-based characterization technologies, this first goal can be realized. The development and progression of this thesis was directed at providing the tools to the decision-maker in order to make this goal a reality.

The second goal was to provide a method for using the data that will be obtained from the site characterization to establish the risk of sites or set risk-based corrective action levels for sites. Three methods were proposed that met this stated goal. These methods provided the flexibility required to overcome potential gaps in data and information due to the constraints inherent in DoD environmental operations in the ROK, while still providing a useful mechanism for determining priorities and allocating scarce resources.

Combined, these two goals reflect the need to provide tools to DoD decision-makers in the ROK (primarily USFK) that they can use and methods they can implement in order to determine the extent of environmental problems. Through this determination, DoD decision-makers in the ROK will then have what they need most - data -- and they

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can utilize that data in order to develop an intelligent environmental policy. Taken as a conceptual whole, that is the direct focus of this research effort.

B. Site Characterization

The primary sources of contamination were reported and some conclusions drawn. From the data compiled during the site visit, 68 percent of the sources of contamination were due to system failures or system component failures. In order to reduce this percentage as well as the likelihood of future sites of contamination, resources must be appropriately allocated toward comprehensive infrastructure upgrades, such as UST and aboveground storage tank (AST) replacement or upgrade and bulk POL storage and distribution system upgrades. Accidents will always occur, but a review of operating procedures and establishment of operating instructions for recurring problem areas (such as heating oil contractor overfills) can help to reduce this percentage. Review spill logs and spill reports for trends in cause, and if apparent, resources should be focused on alleviating the cause.

Fuel-related contaminants comprised 70 percent of known contamination at hazardous waste sites, while VOCs accounted for an additional 22 percent. This large proportion of the potential contamination should be strongly considered when actual decisions are made concerning specific technologies to utilize for site characterization. Understanding that resources are scarce and policy support light, decision-makers must make intelligent decisions with potential future monies. Of this 70 percent of fuel contamination, 65 percent (or approximately 45 percent of all sites) was attributable to diesel contamination. Being aware that diesel is currently necessary for heater and boiler

units, attention should be focused on the root causes of this diesel contamination and remedies proposed.

Although not unexpected, the available site characterization data at DoD installations in the ROK ranged from reasonable to nonexistent. Before site characterization work can proceed, decision-makers must have information concerning the number and location of potential hazardous waste sites, the potential contaminants present, and any relevant supporting data. Only in this manner will the decision-maker be able to determine a credible course of action and appropriately allocate scarce resources.

Innovative site characterization technologies selected for evaluation, as previously stated, were drawn from USEPA sources, from NHSRC sources, from USAF AFRL sources, and through support from the body of literature. The author understands that opinions may differ as to the current status of some of the innovative technologies (i.e. some listed as innovative may be considered as emerging in some aspects by others) and as to the applicability of some of the innovative technologies (i.e. some listed as useful in certain media or listed as a field-based technology may be disputed by others). However, all the technology choices that were evaluated were supported by literature and by field data, and thus were included for possible implementation.

Decision-makers must understand that the field of environmental sensing technologies is an extremely dynamic one. The technology of today may easily be superceded by a far superior technology only a year or less from now. The reader should recognize that the technologies described and the data utilized to illustrate their capabilities have a shelf life. Not only will the quality of data provided by the

characterization technologies improve with time, but limitations and barriers may be overcome as well. This could present a significant change to the results reported herein. In addition, if a better technique or instrument is disCVered and proven, the technology may be replaced completely or utilized only sparingly. Thus, the reader should understand that limitations exist on the use of the data reported for the various technologies within the literature review.

C. Risk Evaluation

Risk assessment and RBCA method, as previously stated, provide varying degrees of useful output depending upon the data and information input, the model or method used, and decision-maker needs. Three methods were proposed for use and evaluated for applicability in this research. As stated, a myriad of methods, both for risk assessment and RBCA currently exist and could be utilized if the decision-maker notices requirements not fulfilled by the proposed methods. The proposed methods were selected, however, due to the fact that an overabundance of site information is not required for their implementation. Whatever risk assessment or RBCA method is ultimately chosen for use, the requirement for data and the likelihood of obtaining the required data must be considered prior to implementation.

The advantages and disadvantages of the risk assessment and RBCA methods were discussed. One essential element necessary for DoD installations in the ROK is flexibility. Various installations have different situational constraints, have varying degrees of contamination, have varying degrees of vulnerability, and in essence, have varying degrees of need for expending characterization resources. Decision-makers need

a flexible yet widely applicable method in order to successfully address the wide range of sites and situations inherent with DoD operations in the ROK.

D. Analytic Hierarchy Process

The AHP was chosen as the MCDM method of choice due to its inherent flexibility, its acceptability by the decision-maker, and its ability, without undue effort, to capture the decision-maker's true preference structure. Alam and others suggest that the AHP has been so popular due to its ability to handle inconsistency in judgements, its ability to incorporate intangible or non-quantifiable criteria in the decision-making process, and its ease of use (Alam, et al, 1997:69). While compromise programming, goal setting, and value function construction were available MCDM methods, they did not meet the particular needs of this researcher or the needs of the decision-maker in this case.

This thesis utilized a comprehensive pair-wise comparison survey in order to elicit the decision-maker's preference structure concerning criteria and alternatives. This survey, while not extremely complex, required considerable time and effort on the part of the decision-maker. For complex hierarchies (where the number of alternatives is greater than 7), the clusterization of alternatives is an option proposed by Saaty and tested by Alam. The need to reduce the number of pair-wise comparisons will help minimize the labor and time in constructing pair-wise comparison matrices, and will provide for greater consistency. Future users of the AHP should consider this valuable option when developing surveys.

Criteria against which alternatives were evaluated were selected to represent or capture the relevant considerations in comparing the alternatives against the stated goal.

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The criteria selected by this researcher and approved by the decision-maker attempted to capture the essence of relevant considerations in alternative evaluation; however, follow-up discussions with the decision-maker (although not performed) could have provided an assessment of how well the decision-maker's needs were met and what additions, deletions, or improvements could be implemented.

Consistency of pair-wise comparisons is an important concept to ensure the decision-maker understood the information provided on the criteria and alternatives and was able to synthesize this information into credible judgements. While the AHP does not insist on perfect consistency, large inconsistencies reflect poorly on the validity of the decision-maker's responses. Consistency of the decision-maker in completing the AHP survey for this research effort was acceptable. Over 90 percent of the various comparison matrices exhibited a consistency index of 0.10 or less. The remaining 10 percent had consistency indices ranging from 0.13 to 0.25. While re-accomplishment of those pair-wise judgement matrices with inconsistencies greater than 0.10 could have been performed to achieve more consistent results, they were not deemed sufficiently detrimental to significantly affect the results, and thus were not re-accomplished. In addition, inconsistencies were much more prevalent in the pair-wise judgement matrices with greater than six comparisons and almost non-existent in those matrices with less than six comparisons.

Ranking of alternatives are strongly impacted by the information that is provided to the decision-maker in order to explain how they work, explain their capabilities, and discuss their limitations. While an attempt was made to extract as much applicable data as was available for each of the innovative field-based site characterization technologies

and risk assessment/RBCA methods, gaps in these data had the potential to directly influence decision-maker preferences. Thus, acknowledgement that the decision is only as good as the data and information that support it is applicable in this case.

E. Alternative Evaluation

The evaluation of the various innovative field-based site characterization technologies and risk assessment/RBCA methods revealed a great deal of information concerning the needs and priorities of DoD decision-makers in the ROK. As demonstrated, the AHP was utilized to elicit the decision-maker's needs and priorities in developing a preference structure. Through the use of ExpertChoice software, the various criteria weights and alternative values were determined. These weights and values, while providing 'answers' to the decision-maker concerning preferred alternatives, also provided insight into the motivation behind the decisions. Discussion of the findings derived from the evaluation follows.

The first comparison was of the criteria weights for the sites with soil contamination. Resources, data quality, and method limitations were weighted as .260, .413, and .327, respectively, for vulnerable sites with soil contamination (with the exception of pesticides, which was weighted as .097, .570, and .333, respectively), while the criteria were weighted as .500, .250, and .250, respectively, for non-vulnerable sites with soil contamination. This data shows that for sites where large populations could potentially be exposed, data quality is most important, and thus, obtaining reliable data to accurately assess the situation is critical. However, for those non-vulnerable sites, efficient allocation of resources takes precedence.

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Another comparison of criteria weights was performed for sites with groundwater contamination. Resources, data quality, and method limitations were weighted as .105, .605, and .290, respectively, for vulnerable sites (with the exception of pesticides, which are weighted as .067, .715, and .218, respectively), while the criteria were weighted as .260, .413, and .327, respectively, for non-vulnerable sites. Similar to soil contamination, data quality takes precedence at vulnerable sites, although in contrast to soil contamination, a focus on data quality also takes precedence at non-vulnerable sites. This finding signifies that groundwater contamination is considered a serious problem or has the potential to cause serious problems with far-reaching impacts. Due to this perception, data quality is paramount to obtaining reliable information in order to accurately assess the situation.

Comparing and contrasting vulnerable sites with soil and groundwater contamination provided additional insight. For vulnerable sites with soil contamination, resources, data quality, and method limitations were weighted as .260, .413, and .327, respectively (again, with the exception of pesticide contamination), while for vulnerable sites with groundwater contamination, the criteria were weighted as .105, .605, and .290, respectively. While data quality took precedence in both cases, this criterion is given much larger weighting for groundwater than for soil. Again, this reflects the desire for an accurate assessment at all sites, with a particular emphasis at sites with contaminated groundwater. In both cases, method limitations were second in importance, while resources were least in importance. This finding shows that retrieving good data, and making sure that the data can be reasonably retrieved, took precedence over the resources expended to obtain the data.

Comparing and contrasting non-vulnerable sites with soil and groundwater contamination also revealed some findings. For non-vulnerable sites with soil contamination, resources, data quality, and method limitations were weighted as .500, .250, and .250, respectively, while for non-vulnerable sites with groundwater contamination, the criteria were weighted as .260, .413, and .327, respectively. Criteria weightings for this site type are in contrast to the previous analysis. Here, resources took precedence at sites with soil contamination, while data quality remained the most important criterion at sites with groundwater contamination. Depending upon the contaminant type, the physical and chemical properties of the contaminant, and the aquifer characteristics, this weighting scheme made sense. Groundwater, as a heavily used resource, may quickly reach receptors, while contaminants in soil may be adsorbed and/or degraded prior to reaching groundwater or another pathway to receptors. Thus, saving resources where appropriate while requiring highly accurate data where appropriate made good management sense.

Decision-maker weightings for pesticides at vulnerable sites in both soil and groundwater provided insight into the decision-maker's perception of this class of contaminants. Many pesticides are linked with serious health effects, with environmental persistence, and with a general fear by the public. Due to frequent use and the general difficulties associated with cleanup, it is apparent that the decision-maker placed heavy emphasis on data quality (weight of .570 for pesticides versus a weight of .429 for other soil contaminant classes, and a weight of .715 for pesticides versus a weight of .605 for other groundwater contaminant classes) in order to assess the situation as accurately as possible. This requirement understandably appeared to be relaxed at non-vulnerable

sites, as weights of the three criteria in both media were equivalent to those of the other contaminant classes.

Alternative selections for sites with soil contamination further reveal insight into the evaluation process. The GC with detector, the CPMS, the GFAA, the biosensors, and the colorimetric indicators were preferred for SVOC, fuel, inorganic, explosive, and pesticide contaminants at both vulnerable and non-vulnerable sites with soil contamination, while for VOC contamination, the GC with detector was preferred for vulnerable sites and the FID was preferred for non-vulnerable sites. For those cases where the same alternative was selected, the different criteria weights (e.g. a pronounced drop in the weight for data quality in favor of an increased weight for resources) had not created a change in the preferred alternative, but the different weights resulted in a decrease in preference intensities. For VOC contamination, the FID, which is a relatively low-cost screening method, replaced the GC with detector, which is a much higher cost, quantitative technique.

Alternative selections for vulnerable and non-vulnerable sites with groundwater contamination similarly provided relevant information. The GC with detector was the preferred alternative for VOC and SVOC contamination, while the CPMS, the GFAA, and the biosensors were preferred alternatives for fuel, inorganic, and explosive contaminants, respectively. For pesticide contamination, however, the biosensor was the preferred alternative at vulnerable sites, while the colorimetric indicators were the preferred alternative at non-vulnerable sites. For those cases where the same alternative was selected, the different criteria weights (e.g. a pronounced drop in data quality weight in favor of an increased weight for resources) had not created a change in the preferred

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alternative, but the different weights resulted in a decrease in preference intensities. For pesticide contamination, the significant reduction in data quality weighting and increase in resources weighting favored the lower cost colorimetric indicators over the higher cost, more limited biosensors.

Comparison of vulnerable sites for soil and groundwater was performed. Even with significant differences in criteria weightings between vulnerable sites with soil and groundwater contamination, preferred alternatives were remarkably similar. In both media, the GC with detector was preferred for VOC and SVOC contamination, while the CPMS, the GFAA, and the biosensors were the preferred alternatives for fuel, inorganic, and explosive contamination, respectively. The only difference in preferred alternatives was with respect to pesticide contamination, where the colorimetric indicators were preferred for soil medium and the biosensors were preferred for the groundwater medium. The colorimetric indicators, while apparently not deemed as providing the data quality of the biosensors, require fewer resources and have fewer perceived limitations than the biosensors. These perceptions, in conjunction with criteria weightings, produced the observed results.

Comparisons were then made between non-vulnerable sites with soil and groundwater contamination. Even with evident disparity in criteria weightings, the preferred alternatives were again quite similar. In both media, the GC with detector, the CPMS, the GFAA, the biosensors, and the colorimetric indicators were the preferred alternatives for SVOC, fuel, inorganic, explosive, and pesticide contamination, respectively. The only difference in preferred alternatives was apparent at sites with VOC contamination, where the FID was preferred for soil contamination and the GC with

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detector was preferred for groundwater contamination. Reflecting upon the criteria differences, the much heavier weighting of resources for soil contamination favors the low-cost FID, while heavier weighting of data quality for groundwater contamination favors the accuracy of the GC with detector.

Many hazardous waste sites are quite complex with multiple contaminants, heterogeneous aquifer characteristics, multiple pathways, and potentially multiple receptors. This researcher acknowledges that, in most cases, a single technology will not be adequate to characterize a site; instead, multiple technologies will be required. This fact should not take away from the preferences of the decision-maker, however, when ultimately selecting technologies for deployment. Combinations of preferences would be an acceptable strategy.

The researcher notes that the output from each AHP hierarchy is a discrete alternative. Each hierarchy is assumed to be independent of the other hierarchies, and each preferred alternative is considered independent of the others. In reality, dependency does exist between hierarchies and alternatives. For example, if the GC with detector was selected as the preferred alternative for VOCs and would potentially be on-site, this technology, although not the preferred alternative for SVOCs, fuel, and pesticides, could be utilized in characterizing those contaminants as well. In this manner, a non-preferred alternative may be implemented over a preferred alternative. Real world constraints and decision-maker preferences will shape the course of action.

The determination of a preferred risk assessment/RBCA method involved a single hierarchy, although much information concerning decision-maker perceptions of criteria importance and preferred methods was deduced. In examination of the criteria, policy

and method output were heavily weighted (.455, respectively), while method input was sparingly weighted (.091). This finding was somewhat surprising since resources are known to be constrained in the ROK, and method input would thus be assumed to be allocated a heavier importance than was determined. However, the decision-maker decided that conformance to policy and method output was more critical. In analogy to the technology evaluation, method output is treated similar to data quality and method input is treated similar to resources. Once again, the decision-maker is focused on high quality output versus concerns over input.

The preferred alternative was actually both of the RBCA methods. The conclusion to be drawn from this evaluation is that the decision-maker desires a RBCA method over a risk assessment method. This preference appeared to be a manifestation of the desire to establish a bias for action, in that the decision-maker did not desire a quantitative incremental risk output, but instead desired a corrective action level, based upon risk, that could be applied.

E. Future Research

Future research concerning environmental restoration of hazardous waste sites at DoD installations in the ROK is a distinct possibility. Once site characterization data have been obtained and RBCA levels have been determined, remedial alternatives will require feasibility research, prioritization, and eventual implementation. Understanding the constraints inherent to DoD installations in the ROK, including policy (or lack thereof), resources, and regulatory and enforcement structure (or lack thereof), among others, will strongly influence the potential pool of applicable remedial alternatives or presumptive remedies.

Another avenue of research includes comparing and contrasting views, priorities, and preferences, of DoD environmental decision-makers in the ROK versus DoD environmental decision-makers within the CONUS and other OCONUS locations, such as Europe, Japan, and Central/South America. In this manner, influence regarding criteria weights and alternative preferences can be utilized to isolate and interpret internal and external drivers and philosophy differences. This study in comparing and contrasting results from various locations would help determine if conditions, priorities, and preferences of DoD decision-makers in the ROK are truly different from those of DoD decision-makers elsewhere.

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Vita

    Captain Dean H. Hartman was born on 28 January 1968 in South Ruyslip, England. He graduated from Choctawhatchee High School, Fort Walton Beach, Florida, in 1986 and entered undergraduate studies on a four-year Air Force Reserve Officer Training Corps (AFROTC) scholarship at the University of Florida in Gainesville, Florida. He graduated with a Bachelor of Science degree in Environmental Engineering in May 1991, and received his commission 4 May 1991, through the AFROTC.

    Captain Hartman's first assignment was to the 47th Civil Engineer Squadron, Laughlin AFB, TX, as the lead civil design engineer, and as the environmental compliance manager. Since his first assignment, Captain Hartman has served in a variety of positions, including environmental coordinator at Osan Air Base, South Korea, and Chief of Environmental Plans and Programs and Readiness Flight Commander at Sheppard AFB, Texas. In August 1997, he entered the Graduate School of Engineering, Air Force Institute of Technology.

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APPENDIX 1: Primary Contaminants and Sources of Contamination

Two approaches were used in order to determine the primary classes of contaminants expected to be found at various DoD installations in the ROK. Table 1-1 was derived from information obtained during a site visit to the ROK in September 1998. Listed in the Table are the various locations and types of contamination, including areas of potential contamination, formerly investigated sites, and spill or release locations. This Table is comprised of available data and by no means includes all sites or possible sites at DoD installations in the ROK. The data is, however, in the opinion of the author, fairly representative of the general distribution of contaminant types at the various DoD installations.

Table 1-1. Areas of Potential Concern, Investigated Sites, and Spill Locations At Various DoD Installations in the ROK
(WCFS, 1997; 51 AMDS/SGPB, 1991-1995; 240th CEF, 1997; Oshiba, 1998; 19th TAACOM, 1995-1998; 19th TAACOM, Sep 1996)

DoD Installation/Area	Location/Facility	Contaminant Type(s)
Osan AB	Bldg 1466	Diesel
	Bldg 819	Diesel, Solvents
	Old Fire Training Area	JP-4, Diesel, POL, Solvents
	Bldg 1363	Diesel, VOCs
	Bldg 1122	Diesel
	Bldg 942	Diesel
	Bldg 1073	Diesel
	POL Railhead	JP-4, JPTS
	POL Storage, Tanks 8 & 9	JP-4
	AMC Ramp	JP-4
	1700 Area	JP-4, JP-8
	Bldg 334	Diesel
	Bldg 910	Diesel
	Bldg 251	Diesel
	Bldg 882	Diesel
	POL Storage, Tank 5	JP-4
	Bldg 936	Diesel
	Bldg 371	Diesel
	Bldg 1102/1103/1104	Diesel
	LOX Facility	VOCs
	Water Wells	VOCs
	Old Power Pro Shop	SVOCs
	Mini-mall Area	POLs, Solvents
	Youth Center	Unknown
	Entomology shop	Pesticides, SVOCs

**Table 1-1. Areas of Potential Concern, Investigated Sites, and Spill Locations
at Various DoD Installations in the ROK (Cont.)**
(WCFS, 1997; 51 AMDS/SGPB, 1991-1995; 240th CEF, 1997; Oshiba, 1998;
19th TAACOM, 1995-1998; 19th TAACOM, Sep 1996)

DoD Installation/Area	Location/Facility	Contaminant Type(s)
Osan AB (cont.)	Landfill, Flightline	Unknown
	Landfill, Golf Course	Unknown
	Landfill, Small Arms Range	Unknown
	Small Arms Range	Inorganics
	Bldg 1302	Diesel
	Bldg 1210	Diesel
	Bldg 511	POLs, Solvents
Kunsan AB	Service Station USTs	Diesel, MOGAS
	Service Station Generator	Diesel
	Facility Heating USTs, Basewide	Diesel
	Bulk POL Storage, 2 sites	JP-4, JP-8, Diesel, MOGAS
	Aircraft Pad	JP-4, JP-8, VOCs, SVOCs
	Aircraft Shelters	JP-4, JP-8, Solvents
	Fill Area	Unknown
	Dry Cleaner	Solvents
	Fuel Pipeline Valve Pits	JP-4, JP-8
	Transformer Storage Area	SVOCs
	Co-Located Club	Diesel
	Aircraft Parts Wash Area	Solvents, VOCs
	Base Transportation Bldg	Diesel, POLs
	Base Theater	Diesel
	Command Facility	Diesel, Inorganics
Suwon AB	Bldg 2338	JP-4
	Groundwater Wells 1-4	VOCs, SVOCs
Taegu AB	Groundwater Wells 1-3	VOCs
	Monitoring Wells	JP-4
Koon-Ni Range	Groundwater Wells 1-3	VOCs
Camp Hovey	Bldg S-4230	Diesel
HQ Area III	Bldg 829	Diesel
Camp Castle	Railhead	Diesel

**Table 1-1. Areas of Potential Concern, Investigated Sites, and Spill Locations
at Various DoD Installations in the ROK (Cont.)**
(WCFS, 1997; 51 AMDS/SGPB, 1991-1995; 240th CEF, 1997; Oshiba, 1998;
19th TAACOM, 1995-1998; 19th TAACOM, Sep 1996)

DoD Installation/Area	Location/Facility	Contaminant Type(s)
34th Support Group	Dragon Hill Lodge Expansion	Diesel
	Madison Communications Site	Diesel
	Youth Center Renovation	Diesel
Camp Casey	Bldg 876	Diesel
Camp Page	Bldg 206	Diesel
Camp Hialeah	Bldg 1023/1024	Diesel
Camp Howze	Well 20-441	VOCs, THMs
	Well 4-331	VOCs, THMs
	Well 5-334	VOCs
	Well 6-389	VOCs
	Well 9-540	VOCs
Camp Edwards	Well 4-331	VOCs
	Well 5-336	VOCs
	Well 6-389	VOCs, THMs
	Well 8-539	VOCs
Camp Carroll	Groundwater	Inorganics, VOCs, SVOCs, Pesticides
Camp Market	Vehicle Destruction Yard	Inorganics, POLs

Utilizing the information in Table 1-1, some general statements can be made concerning the types of contamination expected at DoD installations in the ROK. Fuel-related contaminants comprise 70 percent of the contaminants listed in Table 1-1, while VOCs account for 22 percent, SVOCs account for 6 percent, and inorganics, pesticides, and unknowns the remaining 2 percent. Of the 70 percent related to fuel contaminants, 65 percent are attributed to diesel, 21 percent to JP-4/JP-8/JPTS, and the remaining 14 percent to miscellaneous POLS and MOGAS.

Correlation between materials and substances utilized at installations and those wastes that may potentially be released into the environment is the aim of Tables 1-2, 1-3, and 1-4. The data for these Tables were obtained from DRMO annual waste disposal summaries and are intended to summarize the categories of hazardous materials use and the magnitude of hazardous waste disposal. These Tables provide information on what wastes have potential to be released. Of course, the fact that a hazardous substance has been disposed of does not mean that it has been released into the environment. On the contrary, these Tables reflect hazardous wastes that were sent to DRMO for proper disposal. Nevertheless, the Tables show the relative quantities of wastes generated by

DoD activities in the ROK, and it is at least possible that a percentage of these wastes find their way into the environment.

Table 1-2. Fiscal Year 1998 Categories of Hazardous Waste Disposal for Selected DoD Operations In the ROK (DRMO, 1998)

Location	Corrosives (lbs)	Toxics (lbs)	Ignitables (lbs)	Paint/Paint-Related (lbs)	Assorted Solvents (lbs)	Waste Oils/Fuels (lbs)
Area I Support Activity	3960	4859	5000	23800	6700	---
Area III Support Activity	---	4	---	---	3142	300
Area IV, 20th Support Group	110	4566	599	24129	1190	2655
MSC-K, Camp Carroll	63301	978	3257	23151	34915	370
Kunsan AB	6264	343	7321	4410	3747	---
Osan AB	6699	3660	20479	43273	4123	678
Navy, Chinhae	---	2	1521	729	836	287
Marines, 1st Signal Battalion	12900	---	---	---	---	---

Table 1-3. Fiscal Year 1997 Categories of Hazardous Waste Disposal for Selected DoD Operations In the ROK* (DRMO, 1997)

Location	Corrosives (lbs)	Toxics (lbs)	Ignitables (lbs)	Paint/Paint-Related (lbs)	Assorted Solvents (lbs)	Waste Oils/Fuels (lbs)
34th Support Group	11025	---	1600	2000	---	---
Area I Support Activity	6367	900	2170	7160	2540	---
Area III Support Activity	15017	1730	5428	8070	619	4
Area IV, 20th Support Group	10970	3097	1381	16305	1826	9150
MSC-K, Camp Carroll	53758	1265	---	270	38481	---
Kunsan AB	6422	1618	1730	6417	589	973
Osan AB	862	30	215	10682	7359	---
Navy, Chinhae	211	466	1680	594	375	3114
Marines, Pohang Depot	450	---	---	1900	450	---

Note: * Data only available for Oct 96 through Apr 97

***Table 1-4. Fiscal Year 1996 Categories of Hazardous Waste Disposal for Selected
DoD Operations In the ROK (DRMO, 1996)***

Location	Corrosives (lbs)	Toxics (lbs)	Ignitables (lbs)	Paint/Paint-Related (lbs)	Assorted Solvents (lbs)	Waste Oils/Fuels (lbs)
16th Medical Logistics Battalion	318	---	405	---	---	230
34th Support Group	18900	---	1512	---	---	---
DPW, Area I East	730	---	---	200	940	---
Area IV, 20th Support Group	202	96	160	3803	3562	---
MSC-K, Camp Carroll	51429	3320	5294	12425	30818	---
DPW, Camp Page	1800	---	---	300	450	615
23rd Support Group	13000	20	4700	2403	---	---
501st Combat Support Group	4558	---	1360	1170	1350	8400
Kunsan AB	20368	19	4522	24321	3657	250
Osan AB	28150	---	---	35	---	517
Navy, Chinhae	99	88	277	486	---	3750
Marines, Pohang Depot	4600	---	---	1400	---	---
Marines, 1st Signal Brigade	99	88	277	486	---	3750

Data for Table 1-5 were obtained from Koon-Ni Munitions Range personnel and is intended to convey average or typical munitions usage at the range. The data can be broadly extrapolated to other ranges on the peninsula. From the data, one can infer the potential for inorganic and explosive contamination at ranges.

Table 1-5. Representative Range Munitions Usage (Stoll, 1998)

Munition	Type	Unit	Monthly Average Use
BDU-33[1]	practice	each	1826
Mark 82[2]	practice	each	19
Mark 83[2]	practice	each	3
Mark 84[2]	practice	each	3
A-10 strafe[3]	HEI	round	20,250
Helo strafe[4]	standard	round	360,000

Notes: 1 – BDU-33 is a practice bomb weighing approximately 30 pounds, primarily composed of steel.

2 – Mark 82, 83, and 84 are full-size steel shapes of 500, 750, and 2,000 pound bombs with one-half to three quarter inch skin filled with concrete.

3 – A-10 rounds are commonly 20 mm high explosive incendiary ammunition containing depleted uranium for penetration and destruction efficiency.

4 – Helo rounds are commonly 7.6 caliber standard munitions rounds.

The previous data provide general information on the primary contaminants that may be expected at DoD installations in the ROK, as well as the sources of that contamination. System failures or system component failures (e.g. UST product feed line to boiler unit breaks) account for 68 percent of the sources of contamination. Accidental spills and releases (e.g. contractor overfill of diesel fuel heating supply tank), with the root problem related to human error, account for 23 percent of the sources of contamination. The remaining 9 percent of the sources of contamination are due to unknown causes (e.g. VOCs discovered in drinking water with no apparent source) or due to practices which were acceptable in the past (e.g. historic contamination from the 1970s or before).

APPENDIX 2: TPH Standard for Contaminated Soil

Soil contamination at DoD installations in the ROK by fuel hydrocarbons is a large problem – perhaps the single largest remediation problem with which environmental personnel on the peninsula must contend (WCFS, 1997; 240th CEF, 1997; Oshiba, 1998). To help deal with this problem, a standard for TPH in soil will be of use. Unfortunately, there is no single, accepted standard delineating how much TPH in soil is "safe." As discussed within the literature review, risk is site specific and a RBCA approach is needed to determine the need for cleanup of soil contamination by fuel hydrocarbons at any particular site. In this Appendix, information is provided that may be useful in implementing such an approach to deal with fuel hydrocarbon contamination.

The Association for the Environmental Health of Soils (AEHS) publishes state-by-state cleanup standards for hydrocarbon contaminated soils and they indicated a continued trend that many of the state programs have changed or are in the process of changing to RBCA approaches (Calabrese et. al., 1997:10). The AEHS noted that most states already provide the option to responsible parties of choosing to determine an alternate cleanup level, under specified conditions, based on a risk assessment of the site. In other cases, the agency in charge has no predetermined standards and makes determinations solely on a site-specific basis (Calabrese et. al., 1997:10). Site-specific considerations may include topography, geology, proximity to groundwater sources or surface water, setting (industrial, commercial, residential), specific pathways (direct exposure, leachability, etc.), land use activities, and type of contaminant(s) present, among others. Table 2-1 provides TPH and related hydrocarbon-contaminated soil standards from a sampling of states.

Table 2-1. State Summary of Soil TPH and Related Parameter Cleanup Standards from a Sampling of States (Calabrese et. al., 1997:10-34)

State	Product	Parameter/ Constituent	Action Level	Cleanup Level
Alabama	Gasoline	TPH	100 ppm	100 ppm[1]
	Diesel	TPH	100 ppm	100 ppm[1]
	Waste Oil	TPH	100 ppm	100 ppm[1]
Alaska	Diesel	Diesel Range Organics (C10-C24)	Site Specific/ 100-2000 mg/kg	Site Specific/ 100-2000 mg/kg
	Waste Oil	Diesel Range Organics (C10-C24)	Site Specific/ 100-2000 mg/kg	Site Specific/ 100-2000 mg/kg
		Residual Range Organics (C25-C36)	2000 mg/kg	2000 mg/kg
Delaware	Gasoline	TPH	100 ppm	Site Specific/ Generally <=100 ppm[2]
	Diesel	TPH	1000 ppm	Site Specific/ Generally <=1000 ppm[2]

Table 2-1. State Summary of Soil TPH and Related Parameter Cleanup Standards from a Sampling of States (Cont.) (Calabrese et. al., 1997:10-34)

State	Product	Parameter/ Constituent	Action Level	Cleanup Level
Delaware (cont.)	Waste Oil	TPH	1000 ppm	Site Specific/ Generally <=1000 ppm[2]
Missouri	Gasoline	TPH	Site Specific	Site Specific 50-500 ppm
	Diesel	TPH	Site Specific	Site Specific 50-500 ppm
North Carolina	Gasoline, Aviation Fuel	TPH	10 ppm[3]	Site Specific[4]
	Diesel, Kerosene	TPH	10 ppm[3]	Site Specific[4]
	Heavy Fuels (Virgin Products)	TPH	> 250 ppm[3]	Site Specific[4]
	Waste Oil	TPH	> 250 ppm[3] > Method detection limit	Site Specific[4]
Indiana	Kerosene, Gasoline	TPH	On-site => 100 ppm; off-site any amount	On-site <= 100 ppm; off-site 20 ppm
	Naptha, Diesel	TPH	On-site => 100 ppm; off-site any amount	On-site <= 100 ppm; off-site 20 ppm
	Waste Oil	TPH	Site specific	On-site <= 100 ppm; off-site 20 ppm
Iowa	Petroleum Contaminated Site	TRPH	3800 mg/kg[5]	Risk-based[5]

Table 2-1. State Summary of Soil TPH and Related Parameter Cleanup Standards from a Sampling of States (Cont.) (Calabrese et. al.,1997:10-34)

State	Product	Parameter/ Constituent	Action Level	Cleanup Level
Nevada	Gasoline	TPH	100 ppm	100 ppm
	Diesel	TPH	100 ppm	100 ppm
	Waste Oil	TPH	100 ppm	100 ppm
Texas	Gasoline	TPH	Product Specific/ Site Specific	Site Specific/ Risk-based[6]
	Diesel	TPH	Product Specific/ Site Specific	Site Specific/ Risk-based[6]
	Waste Oil	TPH	Product Specific/ Site Specific	Site Specific/ Risk-based[6]
Utah	Gasoline	TPH	1500 mg/kg[7]	1500 mg/kg[7]
	Diesel	TPH	5000 mg/kg[7]	5000 mg/kg[7]
	Oil & Grease	TRPH	10,000 mg/kg[7]	10,000 mg/kg[7]

Notes:

[1] - risk assessment may be used for an alternate corrective action limit

[2] - based upon Class B site; Class A sites more stringent, Class C sites less stringent. Factors influencing ratings include well locations, groundwater depth, residential, commercial, or industrial settings, etc.

[3] – phasing out TPH-based action levels and adopting risk-based, compound-specific action and cleanup levels

[4] - utilize a Site Sensitivity evaluation and risk-based levels to determine cleanup levels

[5] – adopted the ASTM RBCA method for addressing Petroleum contaminated sites; listed action levels are used to determine when a Tier 1 investigation is required

[6] – no range available; based upon set organization procedures

[7] - implemented Tier 1 RBCA; cleanup levels are "screening levels" and can only be applied when the Tier 1 worksheet is complete and no receptors are within 30 feet of the source area

The TPH measurement represents the total concentration of a broad spectrum of petroleum hydrocarbon constituents that can be detected by TPH analysis (can be upwards of 250 compounds, depending upon source product). One of the more common TPH soil cleanup standards (although used sparingly as of late) is 100 mg/kg (Boyce and Michelsen, 1993:111). The technical basis for such a TPH standard is generally not presented in the regulations, although one state correlated this standard to the protection of taste and odor qualities of groundwater.

Utilizing a set numerical standard has several important limitations, some of which are listed below. The toxicity and mobility of the specific chemicals present within the detected TPH range may vary widely from site to site (Boyce and Michelsen,

1993:110). Risks reported at TPH sites can vary greatly due to the intereference of many low-risk waste products, such as greases, vegetable oils, and similar products, co-mingled with the hazardous wastes. TPH concentrations reported at different sites may not be comparable because of differences in analytical method used and/or due to potentially significant differences in the degree of weathering and/or transport the petroleum has undergone in the environment (Boyce and Michelsen, 1993:110). In general, generic TPH standards may result in an inefficient allocation of remediation resources because they do not identify and address actual risks at a site, potentially resulting in an overprotective (most often the case) or under-protective (very infrequently the case) cleanup. These deficiencies can be addressed through the use of a RBCA approach that takes into account site- and chemical-specific factors.

Important RBCA parameters discussed in the literature review included identification of potential sources, transport pathways, receptors, and exposure pathways. Characterizing the exposure setting (physical environment, potentially exposed populations) and identifying exposure pathways (chemical source/release, exposure point, exposure route), as described in the literature review, help to determine these parameters. Table 2-2 outlines some common sources, pathways, and exposure routes. Selection of chemical(s) of concern and appropriate RBSLs (commonly a Tier 1 requirement) then follow. This selection of chemicals of concern and establishment of RBSLs may require a departure from a simple TPH measurement to a more defined measurement (e.g. looking for specific aromatics only, looking for PAHs only, looking for C_{16} to C_{21} compounds, etc.).

Table 2-2. Common Chemical Release Sources at Sites in the Absence of Remedial Action (EPA RAG, 1989:6-10)

Receiving Medium	Release Mechanism	Release Source
Air	Volatilization	Surface wastes—lagoons, ponds, pits, spills Contaminated surface water Contaminated surface soil Contaminated wetlands Leaking drums
	Fugitive dust generation	Contaminated surface soil Waste piles
Surface water	Surface runoff	Contaminated surface soil
	Episodic overland flow	Lagoon overflow Spills, leaking containers
	Groundwater seepage	Contaminated groundwater
Groundwater	Leaching	Surface or buried wastes Contaminated soil

**Table 2-2. Common Chemical Release Sources at Sites in the Absence
of Remedial Action (Cont.)** (EPA RAG, 1989:6-10)

Receiving Medium	Release Mechanism	Release Source
Soil	Leaching	Surface or buried wastes
	Surface runoff	Contaminated surface soil
	Episodic overland flow	Lagoon overflow Spills, leaking containers
	Fugitive dust generation/deposition	Contaminated surface soils Waste piles
	Tracking	Contaminated surface soil
Sediment	Surface runoff, episodic overland flow	Surface wastes—lagoons, ponds, pits, spills Contaminated surface soil
	Groundwater seepage	Contaminated groundwater
	Leaching	Surface or buried wastes Contaminated soil
Biota	Uptake (direct contact, ingestion, inhalation)	Contaminated soil, surface water, sediment, groundwater or air Other biota

In order to evaluate human health risk using TPH composition as the basis, the TPH Working Group evaluated three approaches: the indicator approach, the whole product approach, and the TPH fraction approach (Weisman, 1998:5). The indicator approach involves describing the toxicity of the whole mixture by the toxicity of one or more constituent chemicals (e.g. analyzing for benzene and/or benzo(a)pyrene). In this approach, if indicator constituents are not present, there is no toxicity associated with the mixture. The whole product approach involves determining RBSLs (developed from RfDs (reference doses) and RfCs (reference concentrations)) for the entire product (e.g. JP-4, diesel, gasoline) based on the whole product toxicity testing of a representative, unweathered fuel mixture. The TPH fraction approach involves assigning toxicity criteria to well-defined, inclusive groups of constituents (fractions, e.g. C_6–C_7, C_{12}-C_{16}, etc.) based on best available toxicity studies completed on constituents, solvent streams, mixtures, and whole product. The responsible party may also opt to utilize a hybrid of the three (e.g. analyze for benzene, benzo(a)pyrene, and C_{25}-C_{31} compounds), if applicable. Specific RfDs and RfCs for the various indicators, whole products, and TPH fractions can be found in the publication <u>Development of Fraction Specific Reference Doses (RfDs) and Reference Concentrations (RfCs) for Total Petroleum Hydrocarbons (TPH)</u>, which is published for sale by the TPH Criteria Working Group (AFRL HED, 1999). This information was not readily available to this researcher. The three primary approaches are pictured in Figure 2-1 in order to allow qualitative comparisons.

INDICATOR APPROACH

C5   benzene   carcinogenic PAHs   C35

WHOLE PRODUCT APPROACH

C5   C35

RfD for JP-4, diesel, gasoline, etc.

TPH FRACTION APPROACH

C5   C35

RfD = 2.0 weighted mixture   RfD = 0.1 petroleum streams   RfD = 1.0 mineral oil
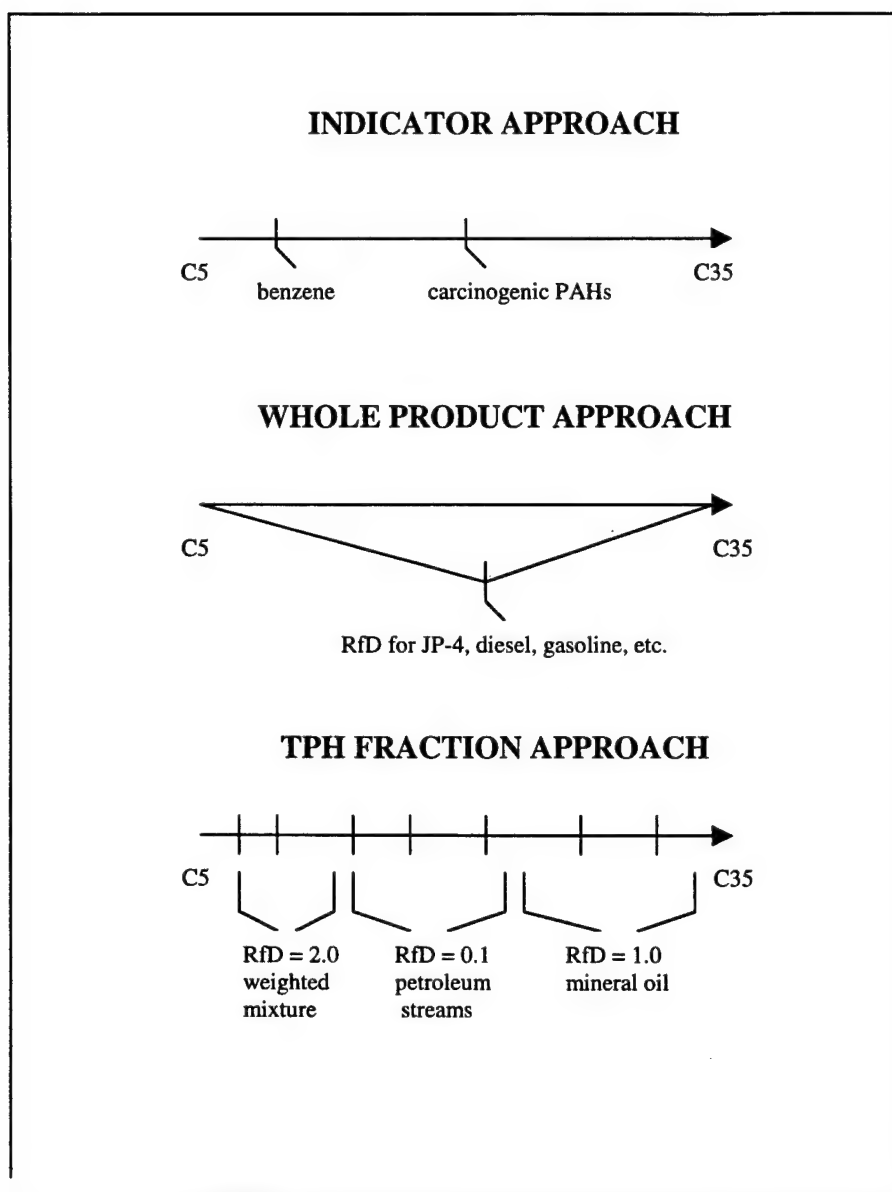
Figure 2-1. Toxicity Assessment Approaches Aiding in RBSL Determination
(Weisman, 1998:5)

Once the RBCA parameters have been determined and RSBLs established, the
RBCA approach, as described in the literature review, may be followed and the need for
specific corrective action levels determined. These same data can then be utilized to
obtain a pool of appropriate remedial technologies (if required) that can be utilized at the
site to meet established corrective action levels.

APPENDIX 3: AHP Survey

General Information.

The information derived from this survey will be utilized to determine the preferred expedient site characterization technologies and risk assessment/risk-based corrective action (RBCA) method in order to ascertain the extent and risk of hazardous waste contamination at DoD installations in the ROK. The survey should be completed as soon as possible, and the agreed upon plan was for the decision-making body to be comprised of individuals (we discussed three, two from USFK-EPO and one from USACE-FED) deemed necessary in order to have needed policy and technology expertise. The body should come to consensus, however, when determining final pair-wise comparison ratings. The survey is lengthy, but will provide an accurate picture of alternatives meeting USFK needs.

The survey first lists important terms and definitions for the various criteria and site characteristics. Following definitions and terms is an example AHP hierarchy aimed at illustrating the relative ease and utility of the process. The last section includes matrices (similar to those shown in the ExpertChoice software) that the 'decision-maker' will complete and return. If possible, the appropriate blocks can be filled with a circle or a square (from MS Word objects menu) or with an 'X', or alternatively the cell color or border can be modified to clearly indicate selection. In this manner, the completed survey can be returned via electronic mail. In lieu of this method, the survey can be completed in pen and returned via normal mail channels (expedited, if possible).

Definitions and Important Terms.

Potentially-Contaminated Site Classifications.
1. *Vulnerable sites* are those sites where access is unlimited, pathways to receptors are evident, and/or the potential to impact large populations exist;

2. *Non-vulnerable sites* are those sites with limited access, pathways to receptors is questionable or does not currently exist, and the site is remote from population centers.

Expedient Site Characterization Technology Comparison Criteria.
1. *Resources* refer to technology equipment and material costs and per sample costs (as applicable), as well as the sampling/analysis time associated with implementation of the particular technology;

2. *Data quality* refers to the type of data produced by the technology (qualitative, semi-quantitative, quantitative), technology accuracy, and technology precision. Accuracy is described in terms of correlation (r) with confirmatory laboratory data (thus, the closer r is to 1.0, the more accurate the technology) and/or the amount or percent of false positives and negatives of the technology, as applicable. Precision is described in terms of the coefficient of variation and relative standard deviation (these measurements are equivalent when relative standard deviation is expressed as a percent, which is the case for this thesis) of the technology as compared to confirmatory laboratory results (thus, lower values for these parameters indicate increasing precision);

3. *Method limitations* refer to the method detection limits, technology dynamic range, geologic/hydrogeologic limitations, and any other pertinent technology constraints.

Risk Assessment/Risk-Based Corrective Action (RBCA) Method Selection Criteria.

1. *Policy* refers to the ability of the method to meet CONUS DoD and USFK risk assessment/corrective action policy needs and requirements;

2. *Method input* refers to the level of data and extent of resources required as input to the method in order to develop a useful risk assessment/RBCA plan;

3. *Method output* refers to the ability of the method to produce a risk assessment/RBCA plan that meets the decision-maker's needs.

Pairwise Comparison Scale. The pair-wise comparison scale shown in Table 3-1 will be utilized by the 'decision-maker' to determine the weight ratios of criteria and alternatives relative to one another. The scale is a tool in helping to quantify the importance of one criterion relative to another and the intensity of preference of one alternative (given a specific criterion) relative to another.

Table 3-1, The Pair-wise Comparison Scale (Saaty DML, 1982:78)

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgement slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgement strongly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgements	Compromise is needed between two judgements
Reciprocals	If activity *i* has one of the preceding numbers assigned to it when compared to activity *j*, then *j* has the reciprocal value when compared to *i*	

Example Analytic Hierarchy Process (AHP) Evaluation.

The following example AHP evaluation is intended to show the decision-maker the basics of how the process works. The figures included are screen prints from the actual ExpertChoice software. Keep in mind that pair-wise comparisons are relative. For example, suppose a decision-maker was comparing the resources of two technology alternatives. Assume Alternative 1 was found to cost $10 per sample and required 10 minutes to run while Alternative 2 was found to cost $20 per sample and required 20 minutes to run. Alternative 1 may not be preferred simply twice as much as Alternative 2. In fact, Alternative 1 may be preferred 3, 4, or 5 times as much or more, depending upon the relative preference of the decision-maker.

Figure 3-1 depicts the initial pair-wise importance comparison of the three criteria (resources, data quality, method limitations) with respect to the overall goal. The goal in this particular example hierarchy is to select the 'best' expedient site characterization technology for a vulnerable, fuel-contaminated site. In this case, the decision-maker determined that resources were twice as important as data quality and method limitations, respectively.

Figure 3-1. Importance Comparison for Hierarchy Criteria

Figure 3-2 illustrates the criteria weights derived from the decision-maker comparisons shown in Figure 3-1.
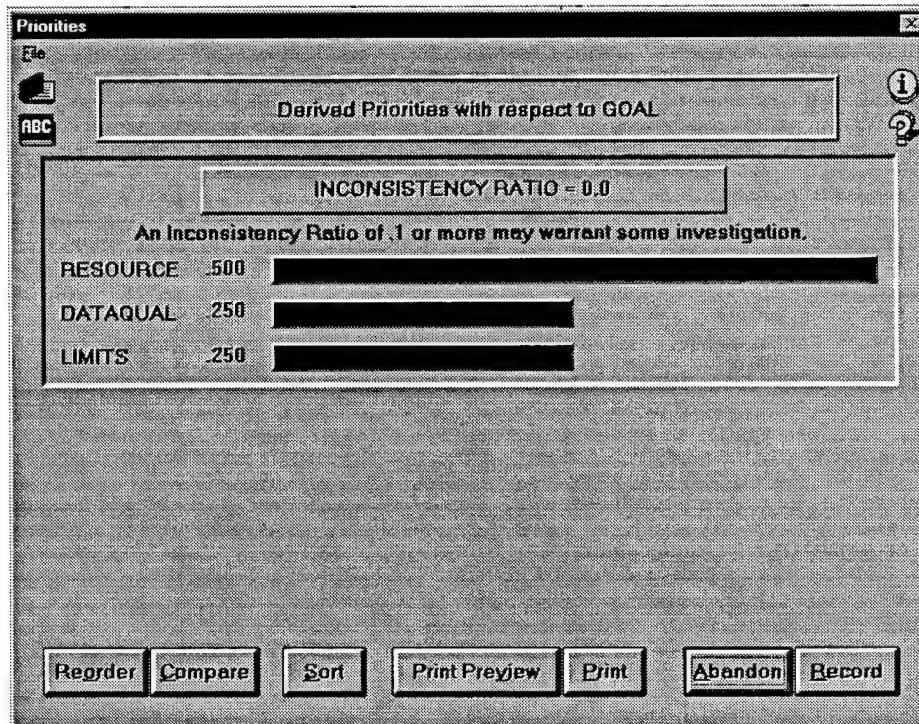
Figure 3-2. Criteria Weights

Figure 3-3 depicts the relative preferences of the alternatives, in a pair-wise comparison manner, with respect to resources. In this case, after reviewing the cost and time elements of the various alternative technologies, the following preferences are selected: the gas chromatograph (GC) is preferred twice as much as the cone penetrometer mounted sensor (CPMS); immunoassay is preferred three times as much as CPMS; soil gas survey is preferred twice as much as CPMS; and so on until all pair-wise comparisons are completed.
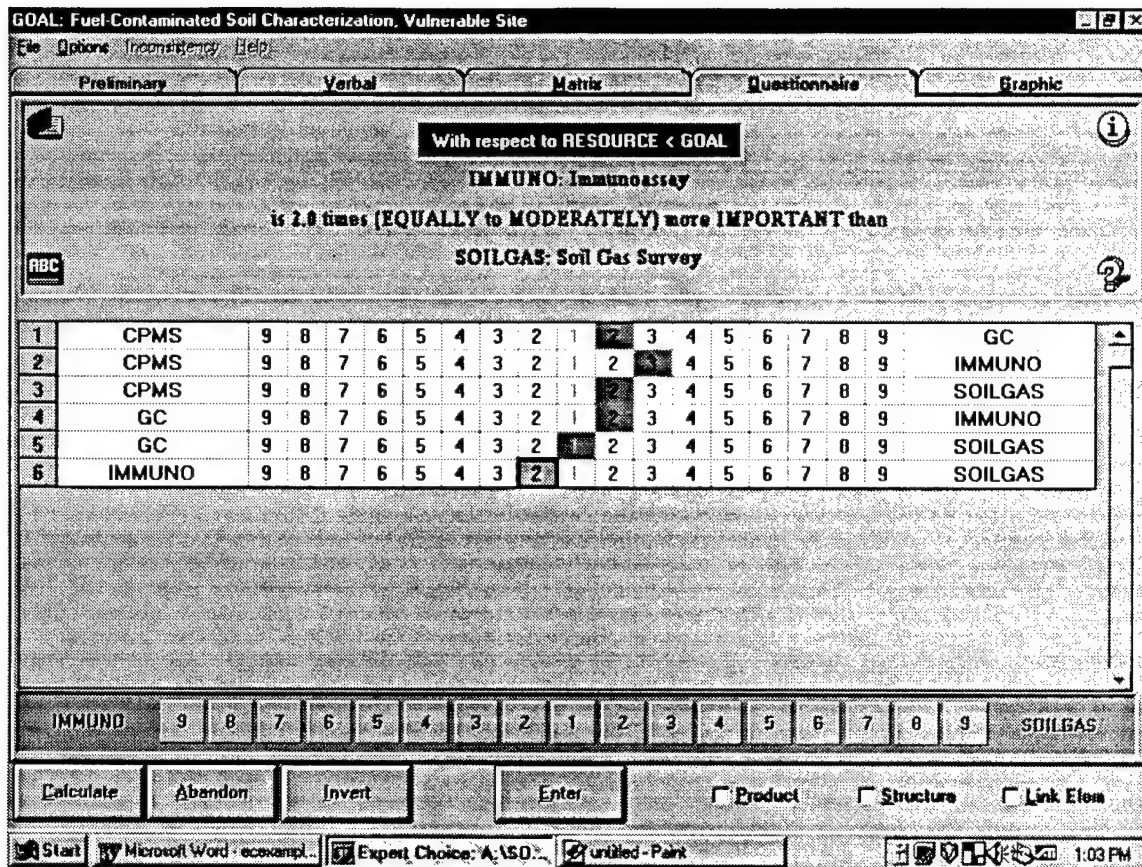
Figure 3-3. Preference Comparisons of Alternatives with Respect to Resources

Figure 3-4 illustrates the resulting weights of the four alternatives with respect to resources.
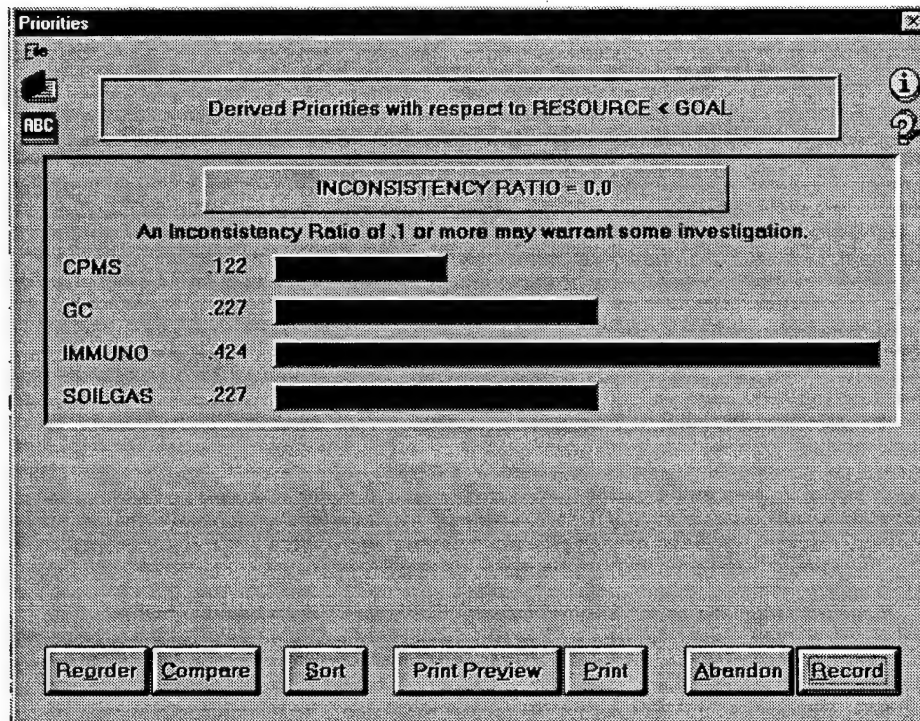
Figure 3-4. Alternative Weights with Respect to Resources

Figure 3-5 depicts the relative preferences of the alternatives, in a pair-wise comparison manner, with respect to data quality. In this case, after reviewing the data type (qualitative to quantitative), the accuracy and the precision elements of the various alternative technologies, the following preferences are selected: the GC is preferred twice as much as the CPMS; immunoassay is preferred equally to CPMS; CPMS is preferred twice as much as soil gas survey; and so on until all pair-wise comparisons are completed.
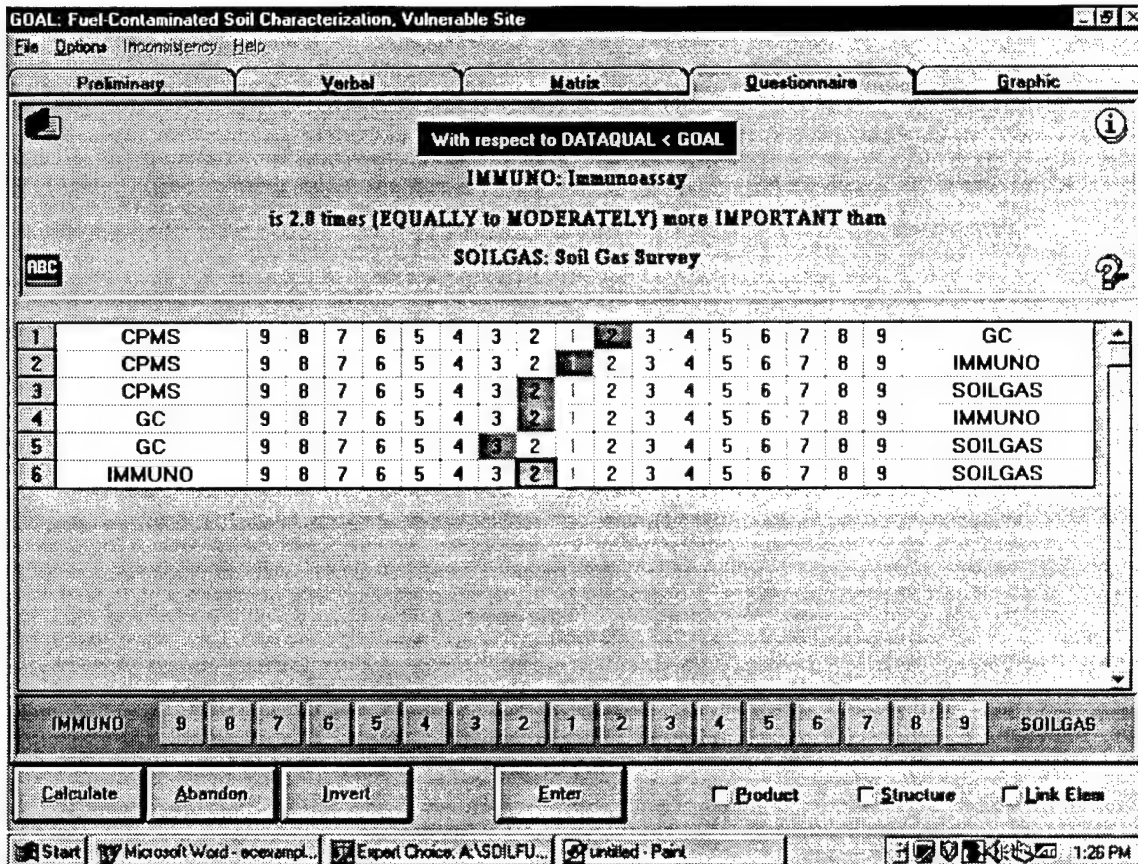
Figure 3-5. Preference Comparisons of Alternatives with Respect to Data Quality

Figure 3-6 illustrates the resulting weights of the four alternatives with respect to data quality.
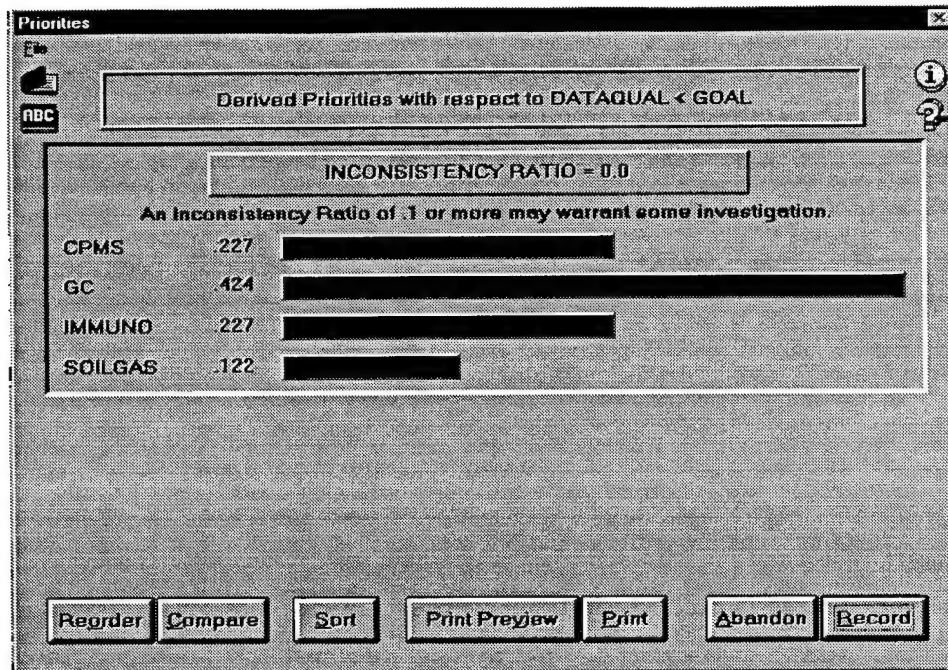
Figure 3-6. Alternative Weights with Respect to Data Quality

Figure 3-7 depicts the relative preferences of the alternatives, in a pair-wise comparison manner, with respect to method limitations. In this case, after reviewing the method detection limit, geologic/hydrogeologic limitation, and any other pertinent limitation elements of the various alternative technologies, the following preferences are selected: the GC is preferred equally to CPMS; CPMS is preferred twice as much as immunoassay; CPMS is preferred three times as much as soil gas survey; and so on until all pair-wise comparisons are completed.
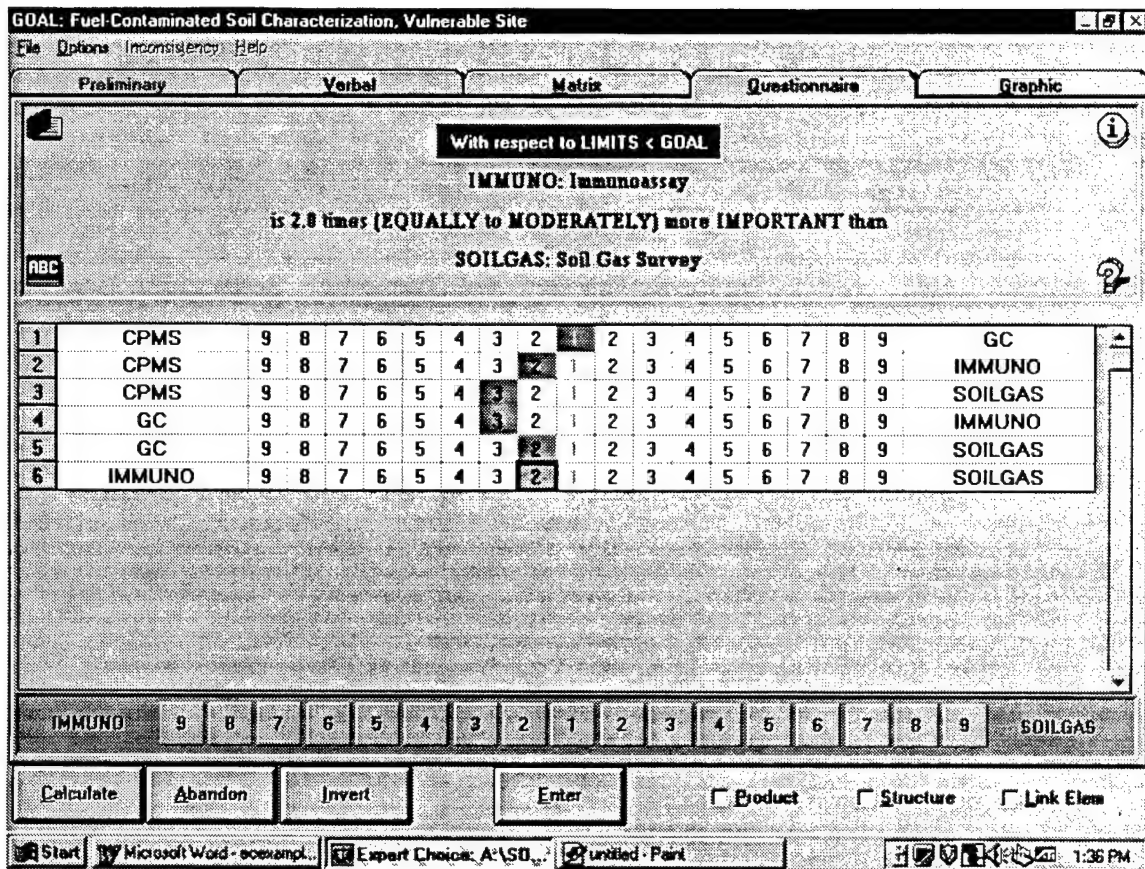
Figure 3-7. Preference Comparisons of Alternatives with Respect to Method Limitations

Figure 3-8 illustrates the resulting weights of the four alternatives with respect to method limitations.
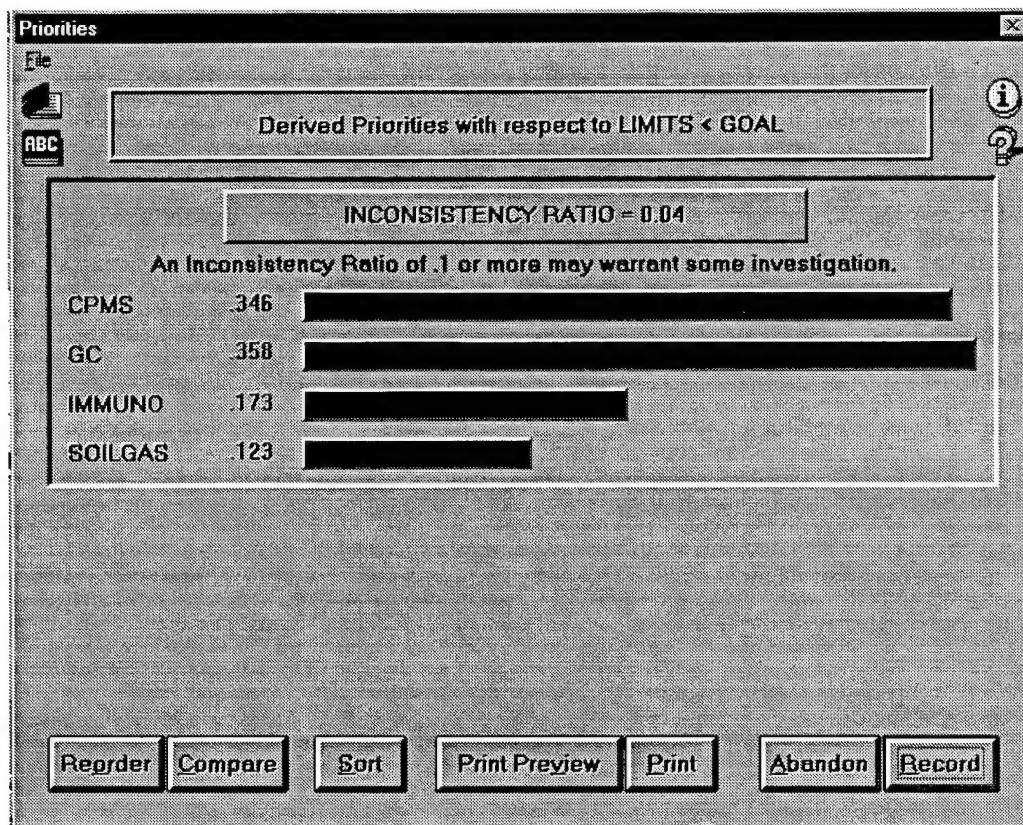
Figure 3-8. Alternative Weights with Respect to Method Limitations

Figure 3-9 depicts the completed hierarchy, with criteria listed below the goal, and correspondingly, the alternatives listed below the criteria.
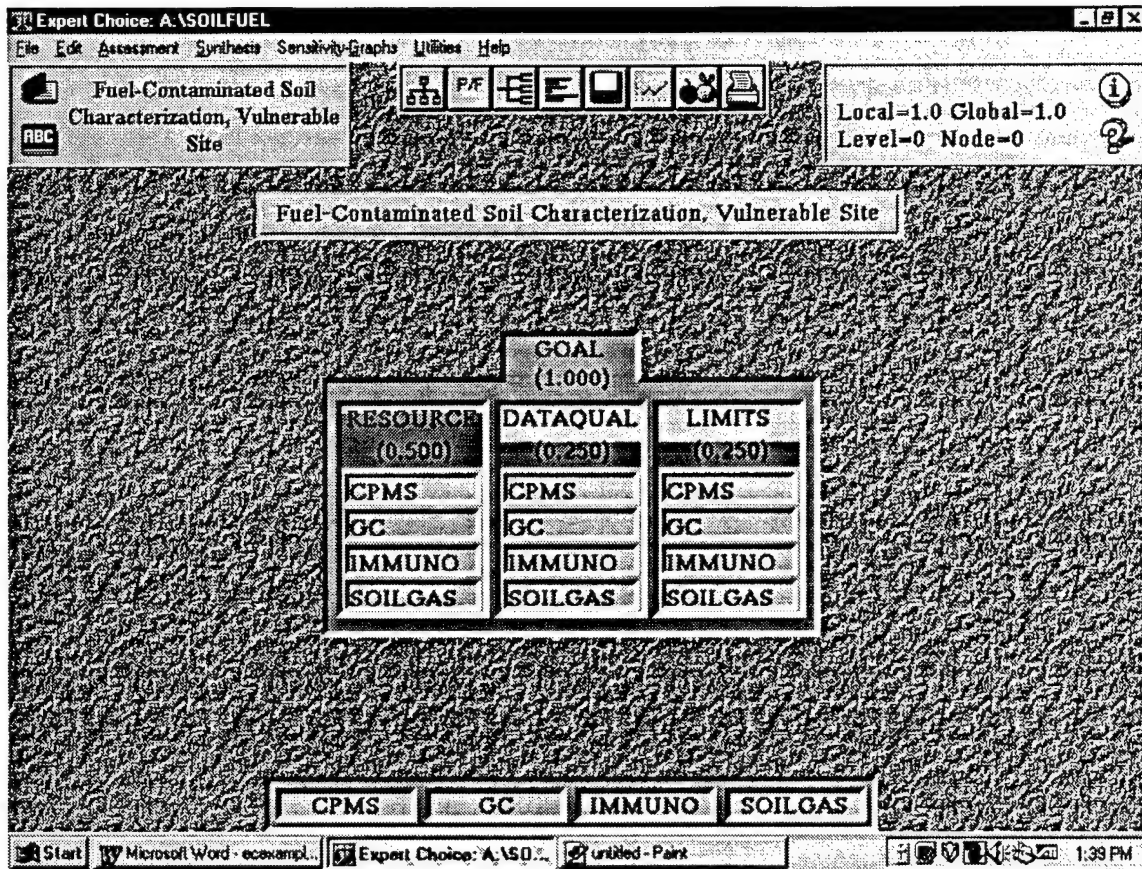
Figure 3-9. Completed Hierarchy

Figures 3-10 and 3-11 depict results obtained from synthesizing all pair-wise comparisons completed by the decision-maker. These figures represent the relative rankings of the various alternatives.
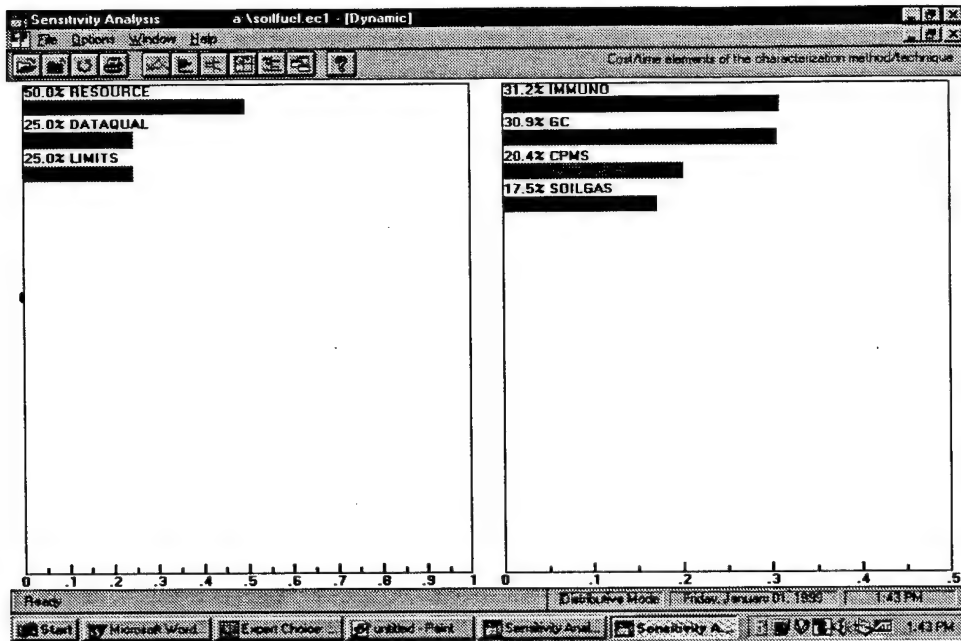
Figure 3-10. Relative Overall Ranking of Alternatives
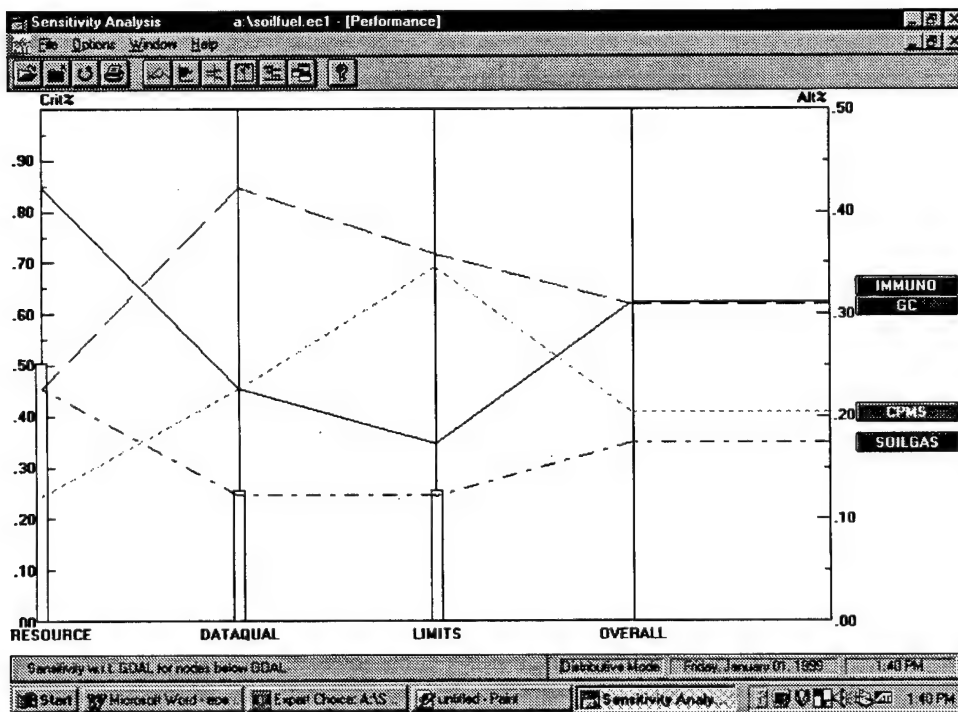
Figure 3-11. Overall Ranking and Criteria Ranking of Alternatives

AHP Survey.

The survey will begin with evaluation of field-based soil contamination characterization technologies at vulnerable sites, continue with field-based groundwater contamination characterization technologies at vulnerable sites, followed by field-based soil contamination characterization technologies at non-vulnerable sites, and field-based groundwater contamination characterization technologies at non-vulnerable sites, and conclude with the evaluation of risk assessment/RBCA methods.

Site Characterization and Technology Evaluation.

Part 1: Soil Contamination, Vulnerable Sites, Various Contaminants.

Soil VOC Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	*⇐ Importance*									*Importance ⇒*								*Criteria*
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations[1]
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Notes: [1] – Method Limitations

Soil VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative		⟸ Preference Intensity								Preference Intensity ⟹								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector[1]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS[2]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID[3]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID[4]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric[5]
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Notes:

[1] – gas chromatograph with detector (commonly mass spectrometry)
[2] – cone penetrometer mounted sensor
[3] – flame ionization detector
[4] – photoionization detector
[5] – colorimetric indicators

Soil VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity										Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance										Importance ⇒							Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Fuel Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Soil Fuel Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	·3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Fuel Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Inorganics Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Inorganics Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Soil Inorganics Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Soil Inorganics Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Soil Explosives Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒							Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Explosives Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Soil Explosives Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Soil Explosives Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative						⇐ Preference Intensity							Preference Intensity ⇒				Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Soil Pesticide Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria						⇐ Importance							Importance ⇒				Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Pesticide Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative						⇐ Preference Intensity							Preference Intensity ⇒				Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Pesticide Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative						⇐ Preference Intensity							Preference Intensity ⇒				Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Pesticide Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Part 2: Groundwater Contamination, Vulnerable Sites, Various Contaminants.

Groundwater VOC Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Groundwater VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater VOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Groundwater SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GC/detector
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	.4	3	2	1	2	3	4	**5**	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric

Groundwater Fuel Contamination, Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	$\Leftarrow$ Importance									Importance $\Rightarrow$								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Groundwater Fuel Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	$\Leftarrow$ Preference Intensity									Preference Intensity $\Rightarrow$								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Fuel Contamination, Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative			⇐ Preference Intensity										Preference Intensity ⇒					Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	CPMS
Immunoassay	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric

Part 3. Soil Contamination, Non-Vulnerable Sites, Various Contaminants.

Soil VOC Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector[1]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS[2]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID[3]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID[4]
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric[5]
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Notes:
[1] – gas chromatograph with detector (commonly mass spectrometry)
[2] – cone penetrometer mounted sensor
[3] – flame ionization detector
[4] – photoionization detector
[5] – colorimetric indicators

Soil VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity										Preference Intensity ⇒							Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric

Soil SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric

Soil Fuel Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria				⇐ Importance								Importance ⇒					Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative				⇐ Preference Intensity								Preference Intensity ⇒					Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	CPMS
Immunoassay	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric

Soil Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Soil Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Biosensor

Soil Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GFAA
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Biosensor

Soil Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Soil Explosives Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Soil Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	·9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Soil Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Soil Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	\u21d0 Preference Intensity																	Alternative
Biosensor	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Immunoassay

Soil Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	\u21d0 Importance																	Criteria
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Soil Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	\u21d0 Preference Intensity																	Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric

Soil Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	\u21d0 Preference Intensity																	Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric

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Soil Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Part 4. Groundwater Contamination, Non-Vulnerable Sites, Various Contaminants.

Groundwater VOC Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria		⇐ Importance									Importance ⇒							Criteria
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Groundwater VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative		⇐ Preference Intensity									Preference Intensity ⇒							Alternative
Immunoassay	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater VOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative		⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria		⇐ Importance									Importance ⇒							Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Groundwater SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater SVOC Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Fuel Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria				⇐ Importance									Importance ⇒					Criteria
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Groundwater Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative				⇐ Preference Intensity									Preference Intensity ⇒					Alternative
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
CPMS	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Fuel Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	GC/detector
Immunoassay	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	CPMS
Immunoassay	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
Immunoassay	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	PID
Immunoassay	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Colorimetric
GC/detector	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	CPMS
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	FID
GC/detector	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	PID
GC/detector	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Colorimetric
CPMS	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Biosensor
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
CPMS	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
CPMS	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	FID
Biosensor	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	PID
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric
FID	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	PID
FID	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Colorimetric
PID	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Colorimetric

Groundwater Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limitations

Groundwater Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Groundwater Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Groundwater Inorganics Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative			⇐ Preference Intensity								Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	XRF
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ASV
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
XRF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GFAA
ASV	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GFAA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor

Groundwater Explosives Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria			⇐ Importance								Importance ⇒							Criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Groundwater Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative			⇐ Preference Intensity								Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Groundwater Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative			⇐ Preference Intensity								Preference Intensity ⇒							Alternative
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Groundwater Explosives Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
Colorimetric	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay

Groundwater Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	⇐ Importance									Importance ⇒								Criteria
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data quality
Resources	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations
Data Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limitations

Groundwater Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Resources

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Data Quality

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Groundwater Pesticide Contamination, Non-Vulnerable Site
Comparing Relative Preference of Alternatives with Respect to Method Limitations

Alternative	⇐ Preference Intensity									Preference Intensity ⇒								Alternative
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Immunoassay
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
GC/detector	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biosensor
Immunoassay	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric
Biosensor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Colorimetric

Risk Assessment/RBCA Method Evaluation.

Most Appropriate Risk Assessment/RBCA Method
Comparing Relative Importance of Criteria with Respect to the Goal

Criteria	$\Leftarrow$ Importance									Importance $\Rightarrow$								Criteria
Policy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Method Input
Policy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Method Output
Method Input	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Method Output

Most Appropriate Risk Assessment/RBCA Method
Comparing Relative Preference of Alternatives with Respect to Policy

Alternative	$\Leftarrow$ Preference Intensity									Preference Intensity $\Rightarrow$								Alternative
ASTM RBCA[1]	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	DoD RelRisk[2]
ASTM RBCA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA[3]
DoD RelRisk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA

Notes:
[1] – American Society for Testing and Materials (ASTM) Risk-Based Corrective Action Method;
[2] – Department of Defense Relative Risk Evaluation Method
[3] – State of Hawaii Risk-Based Corrective Action Method

Preferred Risk Assessment/RBCA Method
Comparing Relative Preference of Alternatives with Respect to Method Inputs

Alternative	$\Leftarrow$ Preference Intensity									Preference Intensity $\Rightarrow$								Alternative
ASTM RBCA[1]	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	DoD RelRisk[2]
ASTM RBCA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA[3]
DoD RelRisk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA

Preferred Risk Assessment/RBCA Method
Comparing Relative Preference of Alternatives with Respect to Method Output

Alternative	$\Leftarrow$ Preference Intensity									Preference Intensity $\Rightarrow$								Alternative
ASTM RBCA[1]	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	DoD RelRisk[2]
ASTM RBCA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA[3]
DoD RelRisk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI RBCA

APPENDIX 4: Site Visit Trip Report

MEMORANDUM FOR RECORD   12 Oct 98

Subject: Trip Report for Korea Visit to Obtain Data for Thesis

1. Purpose. The purpose of this visit was to gather data relating to risk assessment, site characterization, and cleanup cost estimation of hazardous waste sites at DoD installations in the Republic of Korea. The inclusive dates of the TDY were 16 – 25 September 1998.

2. Travelers. Dr Mark Goltz, Capt Dean Hartman, and Capt Mike Griffin.

3. Discussion.

     a. Yongsan Post. Travelers began the data collection trip at Yongsan Post on 17-18 Sept 98 by meeting with Mr John Anderson, Environmental Chief, and Mr Mark Kwon, Environmental Engineer, of the Eighth US Army (EUSA). Funds for this trip were provided by this office under the hat of US Forces Korea (USFK). Topics addressed included organizational structure of USFK/EUSA, USFK/ROK environmental policy, and objectives of the thesis research. In-depth interviews with the staff and a member from USACE introduced aspects of the Analytic Hierarchy Process (specific multiple criteria decision-making technique), and formalized requirements for site characterization technology and risk assessment. Additionally, discussions of relevant cost models and pertinent aspects of these models were discussed. Travelers briefed the ACofS Engineer (EUSA-EN), COL Moldenhauer, concerning the thesis effort, what benefits could be expected from the effort, and what was to be accomplished during site visits. COL Moldenhauer emphasized the need to ensure the thesis product would be a tool that commanders could use in order to support the need for environmental action and justify needed funding.

     ACTION ITEM: Capt Hartman needs to develop decision-maker survey for USFK to evaluate AHP hierarchies and select best alternatives for site characterization and risk assessment.

     b. USACE-FED Compound. Travelers visited Mr Doug Bliss, USACE-FED, at the FED compound on 18 Sep 98. Discussion focused on obtaining geologic/hydrogeologic data and information from the FED office for installations throughout the peninsula. Mr Bliss stated his office would provide a geologic site summary from each installation where borings or wells had been completed. This information is expected late October 98.

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c. Camp Market. Travelers visited the DRMO-Bupyong compound located at Camp Market on 18 Sep 98. We met with Ms Lori Dwelly, Hazardous Material Specialist, to search for hazardous waste disposal summary data. The idea was to determine what materials/substances installations were using in their operations and disposing of as waste in order to make the correlation with what materials/substances may be present in the environment. The information in question is on file, but was not readily available during the site visit. We await delivery of the information. In addition, contaminated site information from a previous ECAS (72) report, which Mr William Donnelly had previously indicated that he had in his possession, was requested.

d. Osan Air Base. Travelers met with Lt Sarah Berdugo, 51 CES/CEV, on 19 Sep 98, and obtained information from Environmental Flight files and records. Information obtained included listings of possible contaminated sites (primarily POL), available site investigation data, spill reports from WIMS-ES and a spill log, environmental contract report information (including baseline risk assessment data for several sites), Integrated Natural Resources Plan information, and other relevant historical and environmental data. Travelers also met with Mr Yu, 51 AMDS/SGPB technician, to obtain well water monitoring results for various COBs and Ranges.

e. Kooni Range. Travelers met with Mr Harold Stoll, Kooni Range Manager, and Mr Shoemaker, Koonni Range Staff, 21 Sep 98. Kooni Range operations are currently run by Lockheed Martin, under contract to DoD. The range was visited in order to provide data on the method of operation and to discern any potential environmental liabilities. The range contained a strafing area and a strafing/bomb drop island. Data on munitions usage, in order to determine possible lead and depleted uranium contamination, was forwarded by the Kooni Range staff. This data has been extrapolated to provide "representative" usage at the range.

f. Camp Red Cloud. Travelers met with Mr Kim, Sun Ho and Mr Yi, Taek Chu, from the HQ Area I Support Activity, Office of the Staff Engineer, Environmental Office, on 22 Sep 98. Initial discussions focused on the area of responsibility for Area I Support Activities, and specific environmental concerns. No environmental reports or environmental contract documents were available, but Mr Kim suggested site visits to Camp Edwards, Camp Hovey, and Camp Casey. Camp Edwards and Hovey showed evidence of major POL contamination, and will provide an opportunity to apply thesis tools and methods as case studies, while Camp Casey was the site of a POL-contaminated soil landfarm remediation facility.

g. Camp Casey. Travelers, along with Mr Kim and Mr Yi from Area I, were met by Mr Yi, Tu Ha, Chief/COR, Environmental Management Office, Directorate of Public Works, Camp Casey, on 22 Sep 98. We visited the Camp Hovey POL site, which consisted of a large concrete vehicle maintenance/parking ramp. The site previously contained USTs that had stored heating fuel serving several installation facilities. Product had previously been recovered from a man-made sump system, and was evidenced from seeps in the hillside adjacent to the river. Mr Yi, T.H. indicated USACE-FED cost estimates to perform site characterization were $500K. A request was made by Camp Casey and Area I staff for us to provide landfarm treatment optimization information.

ACTION ITEM: Dr. Goltz will provide information concerning landfarm treatment optimization information to Area I environmental staff. and Capt Hartman will provide tank tightness testing information and possible contrators.

h. Camp Edwards. Travelers, along with Mr Kim and Mr Yi from Area I, were met by Ms Pak, the Camp Edwards environmental coordinator, on 22 Sep 98. Data concerning chlorinated hydrocarbon contamination of the drinking water aquifer (as indicated through sampling of the drinking water wells) were requested (and later received). The site visit focused on a POL leak, presumably diesel, from one of the three 210K bulk USTs, although the source was officially unknown. The USTs were located approximately 100 meters up-gradient, and Camp Edwards public works/environmental staff had been collecting approximately 150 gallons of free product per week from several wastewater manholes. The apparent purity of the product indicated the relative speed of movement and extent of the plume. Staff indicated they had programmed for DFSC funds for tank testing and potential remedial action, but funding status was unknown. Camp Edwards staff indicated that the USACE-FED had performed a basic preliminary site investigation, consisting of soil samples, and had indicated the site was contaminated. No further information had been made available, such as the levels of contamination in the samples. The estimate for site characterization from FED was $600K. A request was made by Camp Edwards and Area I staff for us to provide tank tightness testing information in support of their requirements.

ACTION ITEM: Capt Hartman will provide tank tightness testing information and possible contrators to Area I environmental staff.

i. Camp Henry. Travelers were met by Mr Brian Peckins, 19th TAACOM Environmental Chief, on 23 Sep 98. Mr Peckins provided a briefing on 19th TAACOM's environmental program, including projects and funding status. Data obtained during the visit included spill reports/spill investigations, ECAS finding information that justified construction of landfarm facilities, and 19th TAACOM environmental project and programming information. No EPR remediation-coded files/documents were available, nor were any formal site investigation, risk assessment, or cost estimation data/reports. Information was not available on preliminary site investigation data generated by USACE-FED in determining site characterization cost estimates for Camps Edwards and Hovey. Mr Seung Baek, USACE-FED, Chief of Environmental Division, was contacted and the preliminary site characterization information and requirements included in developing the cost estimate were requested.

j. Taegu Air Base. Travelers were met by TSgt Backus and TSgt Berry, 51 MMS staff, on 23 Sep 98. Review of the pump-and-treat system was performed. The system has been in operation since 1982 following a major POL release and facility explosion, with intermittent interruptions in operation. Study of the site has been performed by HQ AFMC/CEV, and several monitoring wells exist at the site. Several drinking water wells at Taegu AB are contaminated with chlorinated hydrocarbons (most prominently vinyl chloride). Additionally, it was discovered that personnel from Brooks AFB had recently visited Taegu AB in order to sample the active drinking water wells (sampled wells 3, 5, and 8). As well, a USACE-FED project, Phase II-Construct Air Stripper, Taegu AB, is currently under construction.

k. Kunsan Air Base. Travelers were met by Capt Laura Johnson, 8 CES/CEV, 24 Sep 98. Information obtained included Kunsan AB MAP, Woodward-Clyde site characterization and risk assessment information on five contaminated sites, an AFCEE study outlining AOCs at Kunsan, applicable portions of the Integrated Natural Resources Management Plan, WIMS-ES spill reporting module data, out-year financial plan for environmental projects and resources, and other data applicable to the theses efforts. A site visit to the bulk POL storage area was accomplished to review installation of a bioslurper system. The system was being installed by Brewer Environmental Industries, Inc., Environmental Services Division (Mr Ralph Carson and Ms Myonghee Lee) in conjunction with the USACE-POD (Mr Donald Schlack) and USACE-FED personnel. This project was funded in order to remove POL contamination (vapor phase and free product/dissolved phase) from the aquifer and vadose zone, while preventing contamination of nearby property.

l. The trip concluded upon return to Osan AB, and subsequently Seoul, 25 Sep 98.

APPENDIX 5: Geologic Summary of Select DoD Installations in the ROK

Index Map.

1. Camp Bonifas/ Liberty Bell/Greaves

23. Camps Casey/Castle/Hovey/H220/Nimble

22. Camps Red Cloud/La Guardia/Stanley/ Falling Water/Jackson/Sears/Essayons/Kyle

2. Camps Stanton/Howze/ Giant/GarryOwen /Edwards

21. Camp Page

20. Beason Site

3. Yongsan Garrison

19. Camp Eagle

4. Camp Market

18. Camp Long

5. Suwon Air Base

17. Camp Colbern

16. K-16, Songnam Air Base

6. Camp Humphreys

15. Command Post Tango

14. Osan Air Base

13. Camp Carroll

7. Kunsan Air Base

12. Camps Henry/George/ Walker/Taegu Air Base

11. Camp Hialeah/ Pusan Storage Facility

9. Chinhae Naval Base

8. Kwangju Air Base

10. Kimhae Air Base

Figure 5-1. Installation Location Map

Contributions.

This information was compiled and provided by Mr Pak, Chun-Pom, of the USACE-FED, Foundation and Materials Branch.

General Geology of South Korea.

South Korea is divided into four general tectonic regions: Kyonggi Massif, Ryongnam Massif, Ogchon Folded Belt, and Kyongsang Basin. The Kyonggi and Ryongnam Massifs are composed of polymetamorphosed basement complexes of schist and gneiss of Archean and Paleoproterozoic age. The Ogchon Folded Belt is situated stratigraphically above theses two massif units and is believed to be of Paleozoic age. The Kyongsang Basin is located in the southeastern portion of the Korean Peninsula and is composed of various igneous and sedimentary rocks of Cretaceous to early Tertiary age. And also, Quarternary alkali volcanic rocks are sporadically distributed.

Site Hydrology.

The groundwater table at each of the Camps was reported at the time of drilling. However, the ground water table is expected to fluctuate with seasonal changes in rainfall.
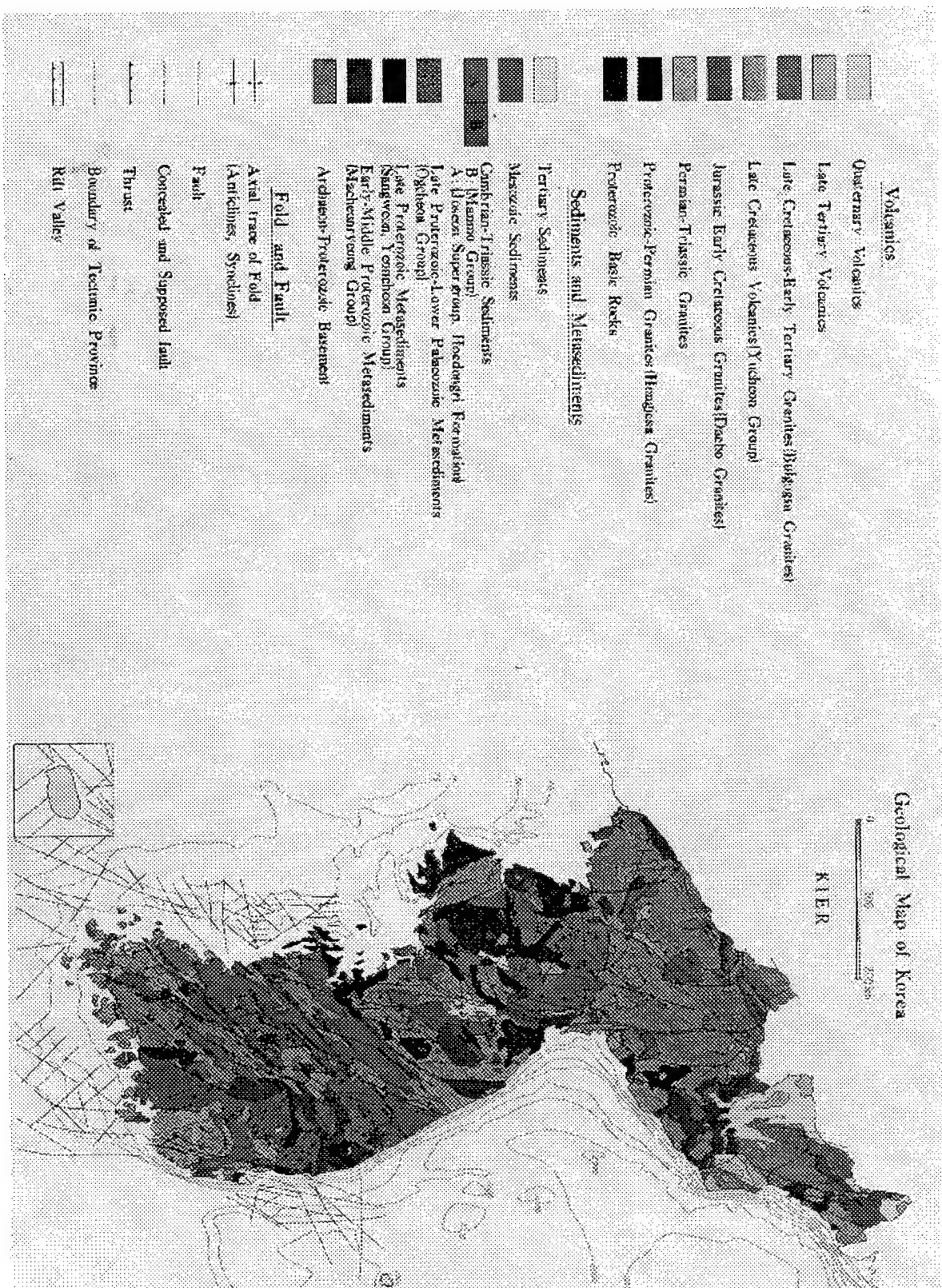
Figure 5-2. Geologic Map of Korea

Panmunchom Area: Camps Bonifas/Liberty Bell/Greaves.

       Topography: These camps are situated on gently sloping terrain surrounded by flat rice paddies.

       Site Geology: This area is located in Granitic Batholith of Jurassic age. The bedrock of this area, except for Camp Greaves, consists of biotite granite. The depth to bedrock ranges from 13 feet to 25 feet at Camp Bonifas and from 4 feet to 25 feet at Camp Liberty Bell. At Camp Greaves the contact zone where Jurassic Granite intruded into Precambrian Kyonggi Gneiss complex can be seen. The bedrock of Camp Greaves consists of biotite schist and biotite gneiss of Precambrian age. The depth to bedrock at Camp Greaves ranges in depth from 9 feet to 30 feet. Overburden is composed of fill, alluvial soil and residual soil. Alluvial soil consists of clayey sand, lean clay and silty sand.

       Site Hydrology: The groundwater table was encountered at various depths ranging between 0.4 and 3.1 feet below ground surface at Camp Bonifas at the time of drilling in 1996. No groundwater was encountered at Camps Liberty Bell and Greaves at the time of drilling in 1985-87 and 1996-1997.

       Referenced Previous F&M Projects: 83-043, 85-042, 87-017, 87-019, 87-020, 96-019, 96-057, and 97-071.

Paju-Munsan Area: Camps Stanton/Edwards/Giant/Garry Owen/Howze

       The area belongs to the Kyonggi massif of tectonic province in Korea and consists of Precambrian rocks of Rangrim Group which is composed mainly of paragneisses, such as biotite gneiss (or schist), quartzofeldspathic gneiss, and migmatitic gneiss with minor quartzite.

Camp Stanton.

       Topography: The Camp is situated along the base and western flank of a minor, north-south trending ridge. The western half of the Camp mainly consists of airfield facilities and occupies a fairly level valley formed by the north-flowing Munsan Area. The ground slopes upward gently to moderately in an eastern direction within the eastern half of the Camp.

       Site Geology: Overburden ranges in thickness from approximately 3 feet to 45 feet in a western direction across the Camp. Thick deposits of alluvium overlying residual soil are contained within the valley of the Munsan River, where the airfield facilities are located. Thin deposits of colluvium, or slope wash deposits, overlie residual soil at the higher elevations of the Camp.

       Site Hydrology: The groundwater table was encountered at depths ranging between 4 feet and 14 feet below ground surface at the time of drilling in 1985-1986.

       Referenced Previous F&M Projects: 85-133 and 85-230.

Camp Edwards.

       Topography: The Camp is situated on a gently sloping terrain surrounded by rice paddies.

       Site Geology: Overburden consists of a thin, discontinuous layer of alluvium and slope detritus underlain by a thicker section of residual soil. There are occasional granitic dykes

that have intruded into the older metamorphic rocks (biotite gneiss and quartzofeldspathic gneiss). The depth to bedrock ranges from 15 feet at the north to 65 feet at the south.

Site Hydrology: The groundwater table was encountered between 4 and 6 feet below ground surface at the time of drilling in 1984-1985; however, no water was encountered at the time of drilling in 1983 and 1987.

Referenced Previous F&M Projects: 83-154, 84-218, 85-154, 87-021 and 87-022.

Camps Giant/Garry Owen

Topography: The Camps are located on flat and gently sloping terrain.

Site Geology: Overburden ranges from approximately 15 feet to 25 feet in thickness. The overburden consists of interbedded layers of very loose to medium dense silty or clayey sand, and silty sand with rock fragments.

Site Hydrology: The groundwater table at Camp Garry Owen was encountered between 8 and 9 feet below ground surface at the time of drilling in 1983 and 1988. The groundwater table at Camp Giant was encountered at approximately 5 feet below ground surface near southern most area, while no water was encountered in at the northern hilly area at the time of drilling in 1982 and 1984.

Referenced Previous F&M Projects: 82-062, 83-086, 83-147, 88-062

Camp Howze

Topography: The Camp is situated in a hilly area which is characterized by moderately high relief ridge lines and narrow intervening gullies.

Site Geology: Overburden consists mainly of residual soil which has developed in place through the weathering of the underlying bedrock. Some colluvium, or slope wash, has been deposited along the small drainage channels. The overburden ranges from approximately 3 feet to 25 feet in thickness across the area.

Site Hydrology: The groundwater table was encountered at various depths ranging between 1.5 and 16 feet below ground surface at the lower relief, while no water was encountered at the high relief at the time of drilling in 1985-1987 and 1998.

Referenced Previous F&M Projects: 85-044, 85-110, 85-172, 85-243 and 97-068.

Yongsan Garrison.

Topography: The compound is situated on relatively flat to gently sloping terrain and hill. The area consists of the Main and the South Post. The South Post is located on alluvial terrace deposits of the Han River.

Site Geology: The bedrock mainly consists of biotite gneiss and quartz biotite schist, which are members of the Precambrian Kyonggi Metamorphic Complex. The metamorphic rock has been locally intruded by dykes of unknown age. The thickness and nature of the soil cover is highly variable across the Yongsan area. The depth to bedrock ranges from approximately 5 feet in the hilly areas to 60 feet at the southern most area, which is covered by Quarternary alluvial deposits that generally increase in thickness as one proceeds in a direction towards the Han River. Residual soil is typically encountered directly above the intact bedrock.

Site Hydrology: Previous investigations in a flat and low relief area indicate the presence of a high, fairly static groundwater table on the order of 2 to 7 feet below the existing ground surface.

Referenced Previous F&M Projects: 85-023, 85-245, 85-252, 87-043, 95-022, 95-062, 95-069, 95-070, 96-015, 96-044, 96-068, and 97-027.

Camp Market.

Topography: The Camp is situated on an alluvial plain which slopes gently downward in a north eastern direction.

Site Geology: Bedrock consists of biotite granite of Jurassic age. The overburden material in this area ranges in thickness from about 12 feet to 30 feet in thickness. The overburden consists of a thick section of alluvial soil underlain by a thin, discontinuous zone of residual soil. The alluvium is composed of an upper layer of clayey soil (CL, CH), underlain by generally cohesionless soil (SM, SC, GP, GM, GC). The residual soil consists of silty sand (SM) and sandy silt (ML)

Site Hydrology: The depth to the ground water table was between 8 feet and 14 feet below the ground surface at the time of drilling in 1985-1988.

Referenced Previous F&M Projects: 85-163, 86-066 and 88-081.

Suwon Air Base.

Topography: The base is located within relatively flat alluvial plain.

Site Geology: Overburden consists of alluvium and residual soil. Alluvial material consisting of clayey sand, gravelly sand, well-graded sand, and silty sand occupy the upper portion of the soil profile. Minor lenses of sandy silt and sandy clay also occur within this assemblage. Residual soil was composed of medium dense to dense, nonplastic silty sand. The thickness of overburden ranges in depths from 28 feet to 33 feet below the ground surface. Bedrock consists mainly of biotite granite of Jurassic age.

Site Hydrology: The groundwater table was encountered between 11 feet and 16 feet below the ground surface at the time of drilling in 1987.

Referenced Previous F&M Project: 86-180.

Camp Humphreys.

Topography: Camp Humphreys is located in the upstream of the Asan-man (Estuary); the flat, lowland plain of western Korea. The elevation varies from 19 feet above mean sea level (MSL) in a marshy area in the western section of the installation to a high elevation of 115 feet above MSL in the extreme eastern corner of the post. Generally, the northern and eastern areas of the installation are slightly higher than the southern and western sections. The portion southwest of the airfield drains to the west or south into low areas of rice paddies crisscrossed by an intricate canal system. Most of the western section drains through canals westward into the Asan-man, which feeds into the Yellow Sea. The southern section drains to the south into the Dunpo-chon (creek), a tributary of the Asan-man. Areas of the installation to the northeast of the airfield drain eastward to the Ansong-chon (creek), also a tributary of the Asan-man. Camp Humphreys is

situated on flat to gently-sloping terrain. The area was used for rice cultivation prior to construction of the camp.

    Site Geology: Overburden materials and bedrock in the vicinity of Camp Humphreys are of variable types and depths. The overburden deposits consist of fill and alluvium overlying a thick section of residual soil. The alluvial soil typically consists of very soft to very stiff, medium to highly plastic clay (CL, CH) containing occasional thin and discontinuous layers of organic sandy silt and peat (OL, Pt). The residual soil generally consists of stiff to very stiff, non-plastic to highly plastic sandy silt (ML, MH) overlying loose to dense silty sand (SM). Surficial deposits of fill have been placed at various locations on the camp for construction purposes. The total thickness of overburden ranges from 24 to 80 feet. Bedrock in the vicinity of Camp Humphreys consists mainly of Jurassic biotite granite with minor Precambrian biotite gneiss primarily distributed around the northern portion of Camp Humphreys. The granite has intruded the older metamorphic rock. The bedrock directly underlying the residual soil was commonly found to range from highly to moderately weathered and soft to medium hard. Hard and slightly weathered rock is encountered at considerably greater depths.

    Extracted from: GIS implementation report

    Referenced Previous F&M Projects for Site Hydrology: A. 96-084; B. 90-050; C. 86-038; D.95-004; E. 96-013; F. 92-004; G.96-011; H. 87-005; I. 85-237; J. 85-214; K. 91-044
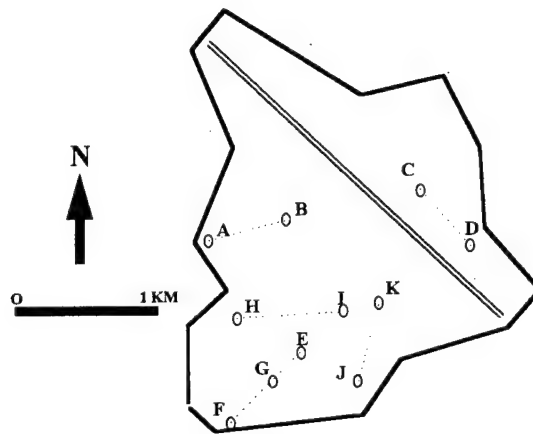
Figure 5-3. Sectional Geologic Delineation of Korea

    Eastern (C-D) section: The depth to the ground water table was approximately 14 feet and 6 feet below the ground surface at sites C and D, respectively. Both explorations were conducted in the month of March, though in different years.

    Western I (A-B) section: The depth to the ground water table was between 51 feet and 59 feet below the ground surface at the time of drilling, which occurred in February and June for sites A and B, respectively.

    Western II (H-I) section: The depth to the ground water table was between 1 foot and 11 feet below ground surface at the time of drilling.

Southwestern (E-G-F) section: The groundwater table was not encountered during the time of drilling at any of these sites. At two sites, area E and G, the drilling had been conducted during a drought. Site F explorations were performed in January 1992.

Southern (K-J) section: The ground water table was encountered at various depths ranging between 2 and 29 feet below ground surface at the time of drilling, which occurred in July 1991 and again in February, August and September 1996.

Kunsan Air Base.

Topography: The majority of the base is located within a relatively flat coastal plain which is bordered by the Yellow Sea on its western border and which extends over ten kilometers inland to the east.

Site Geology: The Kunsan area is tectonically located in the Kyonggi Massif and is predominately composed of mica schist of the Early Proterozoic age Seosan group. Basement rocks found in the vicinity of Kunsan AB include breccias and red/black shale belonging to the Cretaceous Kyongsang Super group and Jurassic to possibly Cretaceous age granite. The shallow subsurface of the central coastal plain is typically composed of marine-derived fine sands and silts. A typical stratigraphic section consists of an upper layer of non-plastic silty sand, often found interbedded with thin layers of clay, which overlies weathered bedrock. The depth to bedrock within the coastal plain ranges from 30 feet to greater than 55 feet below ground surface. The basement rock underlying Kunsan AB ranges from biotite granite in the northern end of the base, a reddish-brown shale underlying much of the middle portion of the base, and a breccia underlying the eastern portion of the Air Base. Surface outcrops of the biotite granite are exposed in the hilly area where the water treatment plant and the north POL facility are located. This granite is estimated to be Jurassic to Cretaceous in age, but no age dating has thus far been conducted. Detailed descriptions of the red-brown shale basement rock is limited to descriptions from deep borings performed near the central part of the base as this unit does not outcrop on the installation. Surface outcrops of the breccia basement rock are exposed in the low hills located at the southern end of Kunsan AB. Within the outcrop, the breccia is observed to be crudely layered with clast-rich zones interbedded with discrete bands composed of a reddish brown silt. The breccia zones include angular clasts of quartzite, shale and sandstone.

Site Hydrology: Groundwater is typically encountered near the surface within the coastal portions of the base. Groundwater depths range from 3 feet to greater than 8 feet below ground surface. This shallow groundwater is typically encountered under unconfined conditions, in moderately transmissive formations consisting of non-plastic, silty sands. Thin layers of clay are often encountered in the subsurface which can create locally confined conditions. This shallow groundwater system is typically 35 to 50 feet thick at the base. According to a prior study by the FED and USACE in 1971, the shallow aquifer at Kunsan Air Base in the upper sandy and silty units is not a viable source of drinking water due to its limited yield. At depth, these marine silty sands encounter the poorly permeable basement formations. The only hydrologic information available for these deeper formations comes from the four deep wells drilled by FED around the Base Command Building. These wells were installed to a total depth of 500 feet into the bedrock shale to achieve a sustainable pumping capacity of 10 gallons per minute per well.

Extracted from the Contractor's report (SOW) of F&M 97-020D

Kwangju Air Base.

Topography: Kwangju AB is situated on a low-lying flat alluvial plain between the Hwang Ryong and Kung Nak Rivers which flow into the Yong San River, with no visible rock outcrops. Kwangju AB is located approximately 6 miles southwest of downtown Kwangju.

Site Geology: The geology of the area is mainly composed of Precambrian granite gneiss, Pre-Jurassic (Triassic-Jurassic) biotite granite and diorite, Cretaceous Yuchon volcanic group and Quaternary alluvium. The overburden material in the vicinity of Kwangju AB consists of a thin upper layer of alluvium underlain by a thicker section of residual soil. The alluvium ranges in thickness from approximately 6 to 9 feet, and is composed of loose to medium dense clayey sand (SC and silty sand (SM), and soft to medium stiff sandy clay (CL). The underlying residual soil consists of medium dense to dense silty, gravelly sand (SW-SM) and silty sand (SM). The depth to bedrock within this area ranges from about 21 to 35 feet below ground surface. Bedrock consists of biotite granite of Triassic to Jurassic age.

Site Hydrology: The groundwater table during the period 1979-1986 was generally very shallow, ranging in depth from about 2 to 6 feet below the ground surface.

Referenced Previous F&M Projects: 82-095, 82-121, 84-181, 85-173, 85-211, 86-081 and 96-076D.

Chinhae Naval Base.

Topography: Chinhae Naval Base is situated on a hill with gently sloping terrain.

Site Geology: The bedrock consists of biotite granite of Cretaceous age. The depth to bedrock ranges from 18 feet below the ground surface at the higher elevations to 60 feet below ground surface at the lower elevations. Overburden consists of alluvium (clayey gravel and lean clay) and various types of residual soil (lean clay, clayey sand, and silty sand).

Site Hydrology: The groundwater table was detected at a depth of ranging from 13 feet deep below the ground surface at the lower elevations in 1990, while no water was encountered at the higher elevations during drilling in 1996-1998.

Referenced Previous F&M Projects: 90-036, 96-016 and 98-063.

Kimhae Air Base.

Topography: Kimhae Air Base is situated on a flat, deltaic area.

Site Geology: The area is located in the Kyongsang Basin and the geology is predominantly composed of sedimentary, plutonic and volcanic rock complex of Cretaceous to early Tertiary age. The bedrock of this area consists mainly of biotite granite with minor andesite. The depth to bedrock ranges from 8 feet to 20 feet below the ground surface. The overburden consists of alluvial soils with sand, sandy gravel, silty clay and silty fine sand.

Site Hydrology: The groundwater table was detected at depths ranging from 0 feet to 5 feet below the ground surface in 1986.

Referenced Previous F&M Projects: 86-004.

Pusan Area: Camp Hialeah and Pusan Storage Facility.

Topography: Camp Hialeah is situated on a flat area within downtown Pusan, while the Pusan Storage Facility is located along the coast.

Site Geology: This area is located in the Kyongsang Basin and is predominantly composed of sedimentary, plutonic and volcanic rock complex of Cretaceous to early Tertiary age. The bedrock of this area primarily consists of andesite and andesitic porphyry of Yuchon Group. The overburden generally consists of fine-grained, cohesive soil that once was deposited at the mouths of several streams that flow into the south sea. The soil is generally very soft and highly compressible, and is composed mainly of medium to highly plastic sandy clay (CL-CH). The thickness of overburden ranges from 18 feet to 50 feet below the ground surface at Camp Hialeah, and from 50 feet to 60 feet below ground surface at the Pusan Storage Facility.

Site Hydrology: The groundwater table was encountered at depths ranging from 2 feet to 27 feet below the ground surface during the period of 1982-1985.

Referenced Previous F&M Projects: 82-051, 84-136, 85-191, 85-194, 85-192, and 85-232.

Taegu Area: Camps Henry, George and Walker, and Taegu Air Base.

Topography: Camps Henry and George and Taugu AB are situated on a generally flat area within downtown Taegu, while Camp Walker contacts the slope of Apsan (Mt.).

Site Geology: This area is located in the Kyongsang Basin and is predominantly composed of sedimentary, plutonic and volcanic rock complex of Cretaceous to early Tertiary age. The bedrock of this area primarily consists of greenish gray and dark gray shale of Taegu Formation. The depth to bedrock increases as one travels from Camp Walker toward Taegu Air Base; ranging from 5 feet at the hill side to 20 feet at basin of Camp Walker; from 16 feet to 24 feet below ground surface at Camps George and Henry; and, from 18 feet to 40 feet below ground surface at Taegu AB. The overburden consists of alluvial soils that have been deposited along the stream channels flowing down from an area of high relief to the south of Taegu, which was underlain by residual soil of bedrock weathering derivatives. The alluvium generally is quite heterogeneous in both lateral and vertical directions. Representative soil type include low plasticity clay (CL), fat clay (CH), clayey sand (SC), silty sand (SM), sandy silt (ML), clayey sand (SC), silty sandy gravel.

Site Hydrology: The groundwater table was encountered at varying depths ranging from 4 feet to 8 feet below the ground surface during the period of 1987-1988 at Taegu Air Base; depths of approximately 16 feet in 1992 at Camp George; depths ranging from 4 feet to 6 feet during the period of 1982-1984 at Camp Henry; and, depths ranging from 10 feet below ground surface to no water discovered during the period 1988-1997 at Camp Walker.

Referenced Previous F&M Projects: 88-107, 94-044, 97-054, 92-052, 87-163, 87-141, .82-104, 85-146, and 86-136

Camp Carroll.

Topography: Camp Carroll is located approximately 1/4 mile east of downtown Waegwan, which is about 19 miles northwest of Taegu City. To the east section of the compound is Santu-bong (Mountain) and Seoul-Pusan Expressway, and to the west is the Naktong-gang (River). The compound is composed of hills and valleys. The elevation of Camp Carroll varies

from 100 feet above mean sea level (MSL) near the main post (in the middle of southern section of the installation) to a high elevation of 286.3 feet above MSL in the extreme northeastern corner of the compound. Generally, the northern and eastern areas of the installation are slightly higher than the southern and western sections. Most of the section drains through canals westward into Naktong-gang, which then flows toward the South Sea. Camp Carroll is situated on flat to gently-sloping terrain. The northwestern and middle southern areas were used for rice cultivation prior to construction of the camp.

      Site Geology: Overburden materials and bedrock in the vicinity of Camp Carroll are of variable types and depths. The overburden deposits consist of fill and alluvium overlying a thick section of residual soil. The alluvial soil typically consists of loose clayey sand (SC) and very soft to very stiff, medium plastic clay (CL) and medium dense silty sand (SM). The residual soil generally consists of loose to dense silty sand (SM) with minor clayey sand (SC). Surficial deposits of fill have been placed at various locations on the camp for construction purposes. The total thickness of overburden ranges from 7 to 45 feet. Bedrock in the vicinity of Camp Carroll consists mainly of Cretaceous biotite granite intruded into older metamorphic rocks distributed around Camp Carroll. The bedrock directly underlying the residual soil consisted primarily of highly to moderately weathered and soft to medium hard. Hard and slightly weathered rock is encountered at considerably greater depths.

      Extracted from: GIS implementation project.

      Site Hydrology: The groundwater table was encountered at various depths.

Osan Air Base.

      Topography: Osan Air Base is located on a flat, alluvial plain, containing some gently sloping hilly terrain. The base is located 378 miles south of Seoul in an agricultural community. The base is bordered on the north by the Chinwi Chon River; on the east by Pyongtaeg-Si, and on the south and west by low hills and cropland.

      Site Geology: Bedrock consists mainly of biotite gneiss, quartzofeldspathic gneiss, and biotite schist, which are members of the Precmabrain Kyonggi complex. There are occasional aplitic dikes that have intruded the older metamorphic rock. The thickness and nature of the overburden material varies with depth and location at Osan AB. Clayey sands and silty sands are most prevalent; however, silty sand gravel, clayey gravelly sand, clay, and silt are also encountered. The thickness of overburden ranges from approximately 10 feet over the high relief, hilly area to as much as 45 feet over the low relief, valley area.

      Site Hydrology: The groundwater was encountered at depths ranging from 2 feet to 20 feet below ground surface.

      Referenced Previous F&M Projects: 85-147, 86-022, 87-084, 93-023, 88-079, 88-004, 86-160, 95-059, 96-025, and 98-057.

Command Post Tango.

      Topography: The area is encompasses a rocky hill and valley.

      Site Geology: The bedrock consists of garnet-bearing biotite gneiss, which is a member of Precambrian Kyonggi Gneiss Complex.

K-16 Air Base.

Topography: The majority of the base is located within a relatively flat, broad alluvial valley. A stream within the valley flows in a northward direction towards the Han River.

Site Geology: Overburden consists of a thick section of alluvium underlain by a thin stratum of residual soil. Alluvial material consisting of clayey sand, gravelly sand, lean clay, clayey sand and silty sand occupy the upper portion of the soil profile. Residual soil is primarily composed of medium dense to dense, nonplastic silty sand. The thickness of overburden ranges in depth from 21 feet to 30 feet below the ground surface. Bedrock consists mainly of biotite gneiss and quartzofeldspathic gneiss, which are members of Precambrian Kyonggi Gneiss Complex.

Site Hydrology: The depth to the ground water table ranged from 6 feet to 15 feet below the ground surface at the time of drilling in 1985, 1990 and 1996.

Referenced Previous F&M Projects: 85-064, 90-019, 96-082, 96-083.

Camp Colbern.

Topography: The Camp is located at a gently sloping hillside.

Site Geology: Overburden consists of alluvium and residual soil. Soil consists of clayey sand, gravelly sand, lean clay, and silty sand. The thickness of overburden increases in depth from 1 feet at higher elevations to 35 feet below the ground surface at lower elevations. Bedrock consists primarily of granitic gneiss of Precambrian age.

Site Hydrology: No groundwater was encountered at the time of drilling in 1985-1987.

Referenced Previous F&M Projects: 84-053, 85-074 and 87-102.

Camp Long.

Topography: Camp Long is situated on a gently sloping hillside.

Site Geology: The bedrock consists of biotite granite of Jurassic age and biotite schist or biotite gneiss of Precambrian age. The contact zone where Jurassic biotite granite intruded Precambrian schist or gneiss was assumed to be located beneath the Camp. The depth to bedrock, in general, is approximately 10 feet below the ground surface. Overburden consists of alluvium (sandy lean clay; clayey sand) and residual soil (silty sand).

Site Hydrology: The groundwater level ranged from 5 feet to 10.5 feet below ground surface at the time of drilling in 1997-1998.

Referenced Previous F&M Projects: 97-017, 98-050 and 98-052.

Camp Eagle.

Topography: The Camp is located within a relatively flat, broad alluvial valley.

Site Geology: The bedrock consists of biotite granite of Jurassic age. The depth to bedrock ranges from 4 feet to 30 feet below the ground surface.

Site Hydrology: The groundwater table was rarely encountered; it was encountered at a depth of 12 feet below ground surface in 1994.

Referenced Previous F&M Projects: 92-048, 94-008 and 94-061.

Beason Site.

   Topography: The site is located at the highest peak (1,157 m in elevation) of Yongmunsan (Mt.), east of Seoul. The site is located on a moderate to steep (20-30 degree) hillside where bedrock is partially exposed at the ground surface.
   Site Geology: The natural soil cover is, in general, discontinuous and thin, and consists of various types of soils including sandy gravel, clayey sand, and silty sand. Bedrock consists of quartzofeldspathic and banded gneiss with minor quartzite. The depth to bedrock ranges from 1 foot to 23 feet below the ground surface.
   Site Hydrology: No groundwater was encountered at the time of drilling.
   Referenced Previous F&M Project: 85-159.

Camp Page.

   Topography: The Camp is located over an alluvial basin within downtown Chunchon.
   Site Geology: Bedrock consists of biotite granite of Jurassic age. The depth to bedrock ranges from the ground surface to 10 feet below the ground surface.
   Site Hydrology: The groundwater table was encountered at various depths ranging from 5 feet to 10 feet below ground surface at the time of drilling in 1984 and 1992.
   Referenced Previous F&M Projects: 84-145 and 92-048.

Uijongbu Area: Camps Jackson/La Guardia/Red Cloud/Stanley/Essayons/Kyle/Sears

   Granitic rocks around the area are part of the Seoul batholith of Jurassic age. The Seoul batholith intruded into the Precambrian Kyonggi gneiss complex and Imjingang Fold Belt, and has a general distribution trend extending in the north to northeast direction.

   Camp Jackson.

      Topography: The Camp is situated on the base of a hill.
      Site Geology: The depth to bedrock ranges from 27 feet to 45 feet below ground surface. Overburden consists of silty/gravelly sand, clayey sand, clayey sand and sandy clay, underlain by residual soil. The bedrock consists of granite.
      Site Hydrology: The groundwater table was encountered at depths ranging from 9 feet to 15 feet below the ground surface at the time of drilling in 1985-1986.
      Referenced Previous F&M Projects: 85-205 and 86-086.

   Camp La Guardia.

      Topography: The Camp is situated on a flat area within downtown Uijongbu.
      Site Geology: The depth to bedrock ranges from 15 feet to 30 feet below ground surface. Overburden consists of silty/gravelly sand, clayey sand, clayey sand and sandy clay underlain by residual soil. The bedrock consists of granite.
      Site Hydrology: The groundwater table was encountered at depths ranging from 8 feet to 10 feet below the ground surface at the time of drilling in 1985; however, no water was encountered in 1986.

Referenced Previous F&M Projects: 85-148 and 86-179.

Camp Red Cloud.

Topography: The Camp is situated on flat to gently sloping terrain within downtown Uijongbu.

Site Geology: Overburden consists of a thin layer of fill, alluvium and residual soil. The surface fill consisted of sand with silt and gravel (SP-SM), clayey sand (SC) and silty sand (SM). This surface fill ranges from 2 to 8 feet in thickness. Beneath this surface fill, sand with gravel (SP) and silty sand with gravel (SM) were encountered. These alluvial sand layers ranged from medium dense to dense consistency. Residual soil consisting of loose to dense silty sand (SM) was encountered below the alluvium. The residual soil was derived from the highly to completely weathered biotite granite bedrock that was encountered at depths ranging from 30.5 to 35 feet below the ground surface.

Site Hydrology: The groundwater table was encountered at depths ranging from 6 feet to 8 feet below the ground surface; however, ground water was not encountered during drilling at some sites.

Referenced Previous F&M Projects: 85-167, 86-116, 97-009 and 97-044.

Camps Essayons/Kyle/Sears.

Topography: The Camps are situated along an elongated, narrow canyon with a gently to moderately sloping hillside.

Site Geology: The depth to bedrock averaged 40 feet below the ground surface, with a maximum depth of 60 feet at Camp Kyle. The bedrock consisted primarily of granite with minor biotite schist. Thick deposits of alluvium overlying residual soil were contained within the valley. Thin deposits of colluvium, or slope wash deposits, overlie residual soil at the higher elevations of the Camps.

Site Hydrology: The groundwater table was encountered at depths ranging from 3 feet at Camp Essayons in 1985 to 15 feet below ground surface at Camp Kyle in 1984. No water was encountered in the hilly area at Camp Sears in 1985.

Referenced Previous F&M Projects: 85-063, 84-115, 85-001, 85-084, 85-215, 85-281, 86-093, and 87-077.

Camp Stanley.

Topography: The Camp is situated along the base of a hill where the ground surface slopes gradually downward toward the northeast.

Site Geology at the vicinity of airfield: The overburden deposits consisted of fill and alluvium overlying residual soil. The alluvial soil typically consisted of medium to very dense sand w/silt, gravel, cobbles and boulders (SW-SM) containing occasional thin and discontinuous layers of sandy silt (ML), clay (CL), and clayey sand (SC). The residual soil generally consists of medium dense to dense silty sand (SM). Surficial deposits of fill have been deposited at various locations in this area. The total thickness of overburden ranges from 25 to 45 feet. Bedrock consists of soft, highly weathered biotite granite. The bedrock directly underlying the residual soil

is commonly highly weathered and soft to medium hard. At the hill, the depth to bedrock is an average of 15 feet below the ground surface.

Site Hydrology: The depth to the groundwater table ranged from approximately 6 feet to 9 feet below the ground surface in the vicinity of the airfield. No groundwater was encountered at a hilly area.

Referenced Previous F&M Projects: 85-067, 87-151, 94-064, ,and 97-039.

Tongduchon Area: Camps Casey/Castle/Hovey/Nimble/H220

Topography: This area is includes a valley and hilly terrain.

Site Geology (Extracted from KIGAM Geologic report (95-033)): Geology of Tongduchon area is composed of Precambrian strata (Kyonggi Gneiss Complex and Imjingang Fold Belt) and Quaternary deposits. Metamorphic rocks of Kyonggyi gneiss complex are comprised of gneiss and schist complex with interbedded marble and quartzite strata. The rocks of the Imjingang Fold Belt are comprised of quartzite and sericite schist. Quaternary deposits can be divided into alluvium and scree according to their geologic origins, and they cover Precambrian rocks.

Precambrian Kyonggi Gneiss Complex: Kyonggi Gneiss Complex covers more than 80 % of the area. Most of the rocks in the Complex are granitic in composition, but its mineral assemblage, mode, texture (grain size, gneissosity, schistosity, development of shear fabric, and presence or absence of feldspar porphyroblasts) are quite variable within the Complex, lending to many compositions such as quartz biotite gneiss, mica schist, migmatitic gneiss, banded gneiss, porphyroblastic gneiss, augen gneiss and calc-silicate rock. Several types of these rocks are mixed and show gradational change even within in a small scale outcrop, and thus their distributions may not be accurately mapped.

Quartz biotite gneiss is ubiquitous throughout the whole area. It is medium grained, and has well developed gneissose fabric. Mica schist is fine grained, shows slaty cleavages, and is invisible to the naked eye. Its typical outcrop and boulders are found near the building 1098. Migmatic gneiss and banded gneiss consist of alternated discontinuous gneissose compositional layers, 1 mm to 3 cm thick, and their typical outcrops are located at the cliff between Camps Casey and Hovey, and along the stream, near the building 480. Porphyroblastic gneiss is normally coarse grained, and contains 10 to 60 percent by volume of alkali feldspar porphyroblasts. Its typical outcrops are observed at the eastern end of Camp Casey, where the rifle ranges are located. Some parts of the gneiss are deformed to augen gneiss. Calc-silicate rock is mainly composed of greenish prismatic amphibole, and was found approximately 50 meters south of building 1124 and near building 187.

At the cliffs or road cuts where wide vertical sections are exposed, total thickness of the completely, hardly and moderately weathered zones of the gneiss and schist complex are normally less than 1 meter. Under these zones, most rocks are either slightly weathered or fresh. The hardness (strength) of fresh rock from the gneiss and schist complex are mostly classified as hard or very hard rock; among these calc-silicate rock is the hardest, however, the mica schist is also moderately hard or hard rock.

Acidic (aplitic, granitic and pegmatitic), intermediate and basic dikes and sills intruded into the gneiss and schist complex, and were frequently found throughout the whole project area. In the migmatitic gneiss region (e.g. cliff between Camps Casey and Hovey), layer or networks of granitic vein formed by local anatexis were found. The age of these dikes, sills and layers are

unknown, but are probably older than that of the Jurassic granite because the foliation of them is cut by the massive granite.

Marble strata are interbedded with the gneiss and schist complex, and details of the distribution included the strike and dip of foliation and dislocation by several sets of faults. They have sharp boundaries with the complex, and their true thickness varied between a few meters to tens of meters. The marble was completely recrystallized medium grained rock, and had a saccharoidal texture. The color of the fresh rock is milky white, light gray or gray, and that of the weathered rock is light brown or brown.

Marble consisted mostly of calcite, and fine grained biotite flakes, while spots of other mafic minerals are rarely discovered. In some sections, the marble exhibits foliation, which is defined by alternative dimensional parallelism of calcite and/or local concentration of mafic minerals. Layers of quartz lenticles that are parallel with foliation of the marble strata were occasionally intercalated, and quartz veinlets, a few centimeters to tens of centimeters in width, intruded concordantly or obliquely into the strata. Typical and fresh marbles were observed in the outcrops near buildings 78, 1047 and 61, and the hardness (strength) of fresh marble was classified as moderately hard or hard rock.

Generally marble was more weathered than many other types of rocks in the area, and dusty calcite granules were easily separated from the weathered marble. Wide, vertical sections of the marble strata, composed of hard and moderately weathered zones, were unable to be delineated completely, and their thickness is unknown. Thick (greater than 5 meters) hardly weathered marble and a formation of red clay (terra rossa: weathering product of marble) were observed at Yondong.

Within the central part of Camp Casey, one quartzite bed has conformably overlain the marble stratum. It sharply contacts the marble stratum, and its true thickness varies between a few meters and tens of meters. The quartzite is pale brown or milky white, well foliated, and consists predominantly of fine grained quartz. Mica-rich cleavage planes that are parallel or perpendicular to schistosity were developed by later strain. A quartz veinlet, a few centimeter in width, trend oblique to schistosity.

Precambrian Imjingang Fold Belt: The southernmost part of the Imjingang Fold Belt is distributed in the northwestern part of the area, primarily Camp Castle. The Belt has conformably overlain the Kyonggi Gneiss Complex, and the trend of the Belt is similar to that of the Complex near the boundary; however, the direction gradually changed to more or less an east-west direction at the northern part of this area.

Consisting metamorphic rocks of the Imjingang Fold Belt are quartzite and sericite schist. Mode of occurrence, hardness and weathering state, texture and mineral assemblage of the quartzite was almost equivalent to that of the interbedded Kyonggi gneiss complex. Sericite schist in the Belt is a well foliated with fine grained rock, and consists mainly of white mica (sericite), biotite and quartz. It is normally moderately or slightly weathered rock, and hardness is classified as moderately hard or hard rock.

Quaternary alluvium and scree: Quaternary deposits in the area were divided into alluvium and scree according to their geologic origins. The alluvium has been deposited in recent geologic time as semisorted sediments or as a fan at the base of the mountain slope. Within the area, this material was found along the stream and within the valley (between the mountain ridges). This formation consisted of unconsolidated detrital materials such as clay, sand, silt, and gravel that were derived mainly from the metamorphic rock. Gravels of granite and basalt were present, but in small amounts.

The scree is a heap of poorly-sorted broken rock fragments from of bedrock and soils that were derived during the comparatively more recent geologic time. The scree was discovered within the small ravine of a project area. Rock fragments were more angular and larger, mostly boulder size, as compared to those of the alluvium.

The depth to bedrock ranged from 5 feet below the ground surface at the higher elevations to approximately 40 feet below the ground surface at the lower elevations.

Site Hydrology: The groundwater table was encountered at varying depths, from a shallow depth near the stream to none being discovered at the higher elevations.
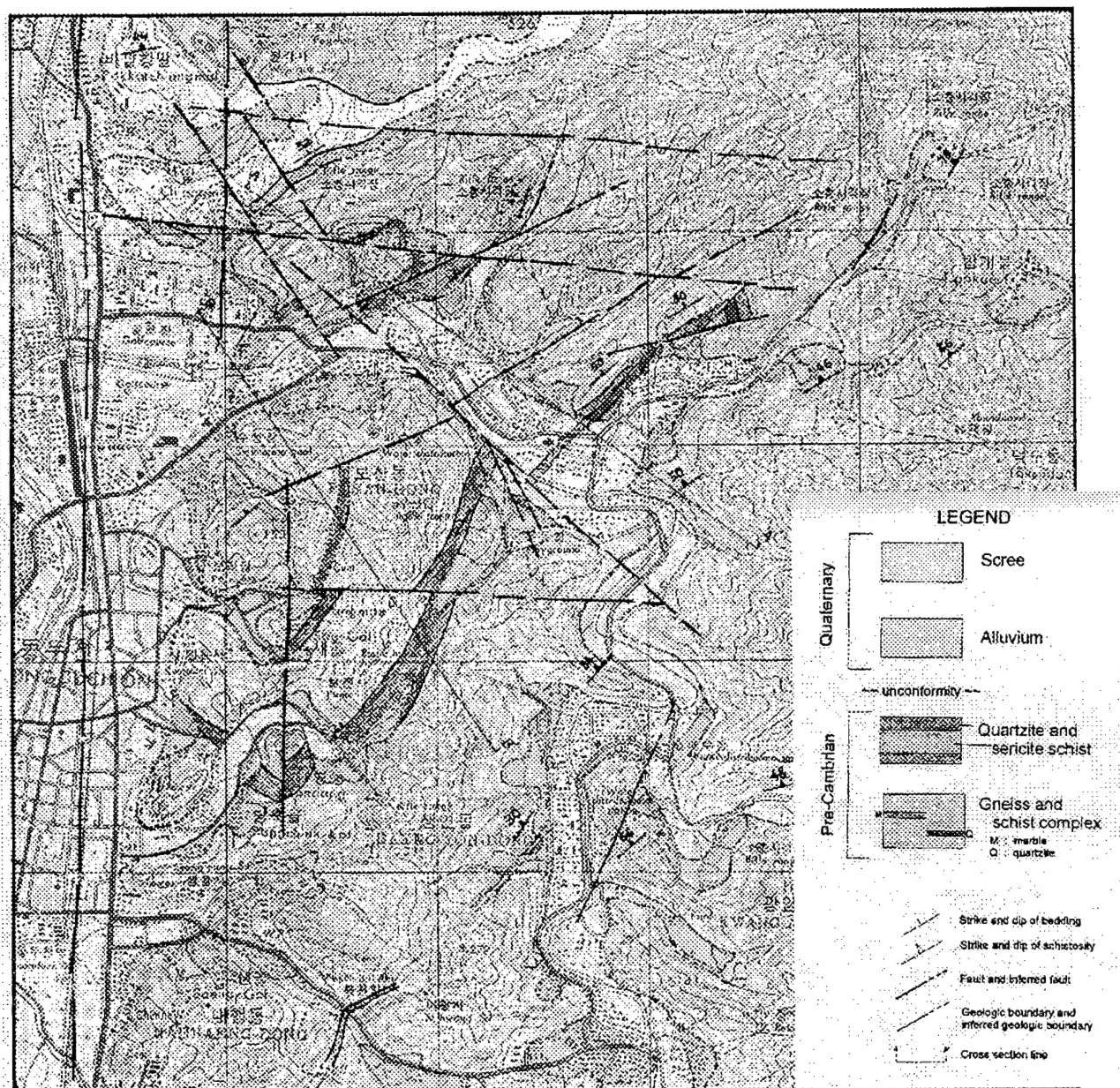
Figure 5-4. Tongduchon Geologic Profile Information

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13. ABSTRACT (Maximum 200 words)

The overall goal of this research was to provide Department of Defense (DoD) decision-makers in the Republic of Korea (ROK) with preferred innovative site characterization technologies and risk assessment methods to meet their needs in obtaining hazardous waste site data and then prioritizing those sites for remediation based upon risk. The study examined the following: primary sources and types of existing contamination at DoD installations in the ROK; available site characterization data; criteria to be used in selecting innovative site characterization technologies; costs and capabilities of the innovative site characterization technologies; risk assessment or risk-based corrective action (RBCA) methods available for employment; criteria to be used in selecting the preferred risk assessment or RBCA method; data requirements and the advantages and disadvantages of the risk assessment and RBCA methods. The Analytic Hierarchy Process was utilized to rank site characterization technologies and risk assessment/RBCA methods preferred for the unique requirements of DoD installations in Korea. Results revealed that the decision-maker preferred innovative site characterization technologies producing data of high quality and a flexible RBCA method that permits the establishment of sound remedial goals. Future research is required to evaluate the feasibility of remedial alternatives once data are collected and policy established.

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